ODC 907.3:187:111:273:425.1

Proceedings of the Conference on

METROPOLITAN PHYSICAL ENVIRONMENT



—Use of Vegetation, Space and Structures to Improve Amenities for People

USDA FOREST SERVICE GENERAL TECHNICAL REPORT NE-25
1977

NORTHEASTERN FOREST EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
6816 MARKET STREET, UPPER DARBY, PA. 19082

The Conference on

METROPOLITAN PHYSICAL ENVIRONMENT

Held at Syracuse, New York
25-29 August 1975

Planned and presented by

Northeastern Forest Experiment Station,
Forest Service, U.S. Department of Agriculture

College of Environmental Science and Forestry,
State University of New York at Syracuse

American Meteorology Society

In conjunction with

The Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Research

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The Conference

by GORDON M. HEISLER, *and* LEE P. HERRINGTON, *Conference cochairmen; respectively research forest meteorologist, USDA Forest Service, Northeastern Forest Experiment Station, Pennington, N. J. 08534; and professor of meteorology, State University of New York College of Environmental Science and Forestry, Syracuse, N. Y. 13210.*

THIS IS A REPORT on the Conference on Metropolitan Physical Environment, held in August 1975 at Syracuse, N.Y., where some 160 scientists and planners met to discuss the use of vegetation, space, and structures to improve the amenities for people who live in metropolitan areas.

Nearly all the papers presented at the Conference are published in this Proceedings. A few of the papers were invited, but most were selected by session chairmen from abstracts submitted. Some presentations were the so-called "poster papers" that provide ample and easy opportunity for direct communication between the author and people particularly interested in the subject.

The conference was held at the Everson Museum in downtown Syracuse. Financial support was provided by the Pinchot Institute for Environmental Forestry Research, Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture. Facilities, local meeting arrangements, and publicity were coordinated by the State University of New York College of Environmental Science and Forestry, as a continuing education service. The American Meterological Society published the complete program in their Bulletin, supplied copies for use at the conference, and later published a conference summary in the Bulletin.

The Pinchot Institute for Environmental Forestry Research was established to develop the knowledge needed to solve problems of policy formulation, land planning, and forest and open-space land management in and around metropolitan areas. It conducts an interdisciplinary research program designed to improve urban living conditions through manipulation of urban vegetation systems.

The Pinchot program is a coordinated effort between the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the Consortium for Environmental Forestry Studies, which is an organization of nine northeastern universities and the Forest Service. The Consortium's Working Group on Urban Forest Amenities is one of eight technical groups through which Consortium research is organized.

The scientists in the Forest Amenities Group have strong interests in the meteorology and acoustics associated with trees and forests in metropolitan areas. Through their research, they are searching for ways to design more comfortable urban environments through manipulation of urban forest systems and open space.

Initial studies of the Amenities Working Group indicated a need for exchange of information and cooperation with other disciplines and with people in other roles — managers, planners, and designers of urban spaces. This conference on metropolitan physical environments was planned to help meet that need.

To broaden the scope of the conference, a number of persons outside the

Forest Amenities Working Group were recruited to serve on the conference program committee. The Conference was organized into eight sessions dealing with four subject areas: (1) urban meso- and micrometeorology, (2) acoustics, (3) air quality, (4) and qualitative aspects of metropolitan environments. The word "qualitative" was used to organize discussion related to the esthetics and function of metropolitan spaces, human behavior, planning, and design.

Conference attendees enjoyed several special events. The eminent ecologist, Pierre Dansereau, of the University of Quebec, set the tone for the conference with an inspiring keynote address at the Monday evening plenary session. Dr. Dansereau stressed the importance of viewing environmental problems holistically and described his conceptual model of global resource interrelationships.

The Wednesday evening banquet address by Paul M. Friedberg, director of the Urban Design Program, City College of New York, was both entertaining and informative. Mr. Friedberg dramatically emphasized the importance of considering human needs and behavior in the design of urban parks and outdoor gathering places. During breaks between sessions, walking tours of downtown Syracuse parks and plazas were led by landscape architecture student Margie Gershek.

In publishing these proceedings, it is the intent of the Northeastern Forest Experiment Station to show more clearly the role of trees in the context of the many physical and social variables of metropolitan environments. Although some of the papers do not deal directly with vegetation, all papers do provide valuable background information for the distinctly interdisciplinary concerns of the emerging field of urban forestry.

Program Committee

Cochairmen of the Conference were:

LEE P. HERRINGTON, State University of New York, College of Enviromental Science and Forestry; and

GORDON M. HEISLER, USDA Forest Service, Northeastern Forest Experiment Station.

Other members of the program committee were:

DONALD D. DAVIS, The Pennsylvania State University (Air Quality Session Chairman).

DAVID DeWALLE, The Pennsylvania State University (Proceedings Editorial Committee).

CHRISTOPHER MACEY, State University of New York College of Environmental Science and Forestry ("Qualitative" Topics Session Chairman).

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DAVID R. MILLER, University of Connecticut (Proceedings Editorial Committee).

GEORGE H. MOELLER, Northeastern Forest Experiment Station.

THOMAS NIEMAN, State University of New York College of Environmental Science and Forestry.

HARRIET PLUMLEY, State University of New York College of Environmental Science and Forestry.

GERHARD REETHOF, The Pennsylvania State University (Acoustics Session Chairman).

ROWAN A. ROWNTREE, Syracuse University (Plenary Session Chairman).

ELWOOD L. SHAFER, JR., Northeastern Forest Experiment Station.

PETER W. SUMMERS, Environment Canada (Meteorology Session Chairman).

MESOSCALE METEOROLOGY OF METROPOLITAN REGIONS

Overview of Urban Climate

by ROSCOE R. BRAHAM, JR., *professor, Department of the Geophysical Sciences, University of Chicago, Chicago, Ill. 60637.*

ABSTRACT. The broad features of urban climate anomalies are described and explained by combining recent METROMEX data with those from prior studies. The urban heat island is well understood, and urban effects upon cloud nuclei and cloud microstructure are clearly observed and explained in part; but the causes of urban effects upon rainfall remain speculative.

IT IS APPROPRIATE that this conference begin with a session on meteorology. Not only are specific climatic effects associated with cities, but meteorological conditions determine the capacity of the atmosphere to transport, disperse, and scavenge pollutants and thereby influence the location and extent of pollution-related injury to plants and man. Moreover, wind and temperature are factors in the dispersal or ducting of sound pollution.

Urban climate is an old subject; published papers go back over 150 years. It is inevitable, therefore, that some of my material will be old-hat to some of you: to others it will provide an entree into the field. However, most of my remarks will center around Project METROMEX and will represent material that has appeared only in specialized publications and reports.

It was about 1968-69 that several scientists engaged in cloud-seeding research began to discuss the need for study of inadvertent modification of weather around large metropolitan areas. Out of this grew Project METROMEX, involving scientists from the Illinois State Water Survey, the University of Wyoming, the Argonne National Laboratory, and the University of Chicago. We undertook a study of the location and magnitude of anomalous weather fields around St. Louis in an effort to establish cause-and-effect relationships linking those fields to causal agents in the city, and to the extent possible to generalize and extend our findings to larger issues in society. Subsequently, we have been joined by scientists from the Battelle Pacific Northwest Laboratories, the Stanford Research Institute, the Sierra Nevada Corporation, and the NOAA Wave Propagation Laboratory.

The metropolitan St. Louis area was selected for study because it was large enough to have a significant pollution problem, yet small enough to be encompassed by a project of practical size. St. Louis has a long history of public concern over pollution; it was the subject of several prior meteorological studies; it has relatively light commercial air traffic, thus making research

flights practical; it was considered to be relatively free of major topographic influences; and it was close enough to Illinois to justify expenditure of substantial amounts of state resources. In addition to support from the State of Illinois, METROMEX is supported by the National Science Foundation, the Energy Research and Development Administration, and the Environmental Protection Agency.

The subsequent choice of St. Louis for the EPA Regional Air Pollution Study (RAPS) has further indicated the appropriateness of St. Louis for such studies and should ultimately enhance the value of both projects. The geographical setting and centers of operations on Project METROMEX are shown in figure 1. Although this project is still in progress, there have been significant findings which, when added to prior data, allow us to determine many of the reasons for urban climate anomalies. Because of space limitations, detailed references to METROMEX publications are not given in this paper. Readers are referred to a recent summary of METROMEX findings and publications *(Principal Investigators of Project METROMEX 1976)*.

For some time it has been known that, in the absence of over-riding topographic influences, cities are warmer than surrounding rural areas. They also have more fog, cloud, and rain, while receiving less sunshine. Cities appear to be drier during summer and more moist

Figure 1.—METROMEX area in eastern Missouri and central Illinois.



during winter than the nearby rural areas. METROMEX has found an excess of thunderstorms and hail downwind of St. Louis.

What can be said about the probable causes of these urban climatic anomalies? Four characteristic differences between urban and rural areas are recognized as potential contributing causes for modifying weather around cities. These four factors are:

1. Contrasting thermal properties of urban-rural surfaces. Most cities abound in rock-like materials whose thermal conductivity and heat capacity are high relative to those of soil and plant materials that dominate the rural scene. These differences have profound effects on urban-rural temperature differences and local convection.
2. Greater aerodynamic roughness of built-up areas. The tall and irregularly spaced buildings of cities represent a much rougher surface, aerodynamically speaking, than do trees and low vegetation. This results in increased mixing (turbulence) and measurable convergence of the low level flow over cities.
3. Smaller amounts of water available for evaporation in cities. In rural areas most of the rainwater remains near the surface and is evaporated or transpired by plants. In cities, much of it is ducted away to non-urban areas for evaporation. The greater use of energy for evaporation results in lower rural temperatures.
4. Anthropogenic heat, gases, and particulates released over cities. Cities release large amounts of heat, gases, and particulates into the air over them. Only recently have we come to recognize the contribution of these to weather effects.

The relative importance of these four factors probably varies with the size and population of a city, its patterns of industry and land use, and with meteorological conditions, both ambient and recent past. We must anticipate that they contribute differently to different weather effects and that their effects combine in different ways depending upon season, time of day, and regional meteorological conditions.

URBAN HEAT ISLAND

One of the longest studied and best understood of the urban weather effects is the *Urban Heat Island.* The characteristics of urban areas invariably result in slight warming of air passing over them during daylight hours and in reduced rates of cooling at night. The result is a shallow pool, or "island" of warm air centered over the city and flowing off as an elevated plume in the downwind direction. (Exceptions are cities under marked topographic influences and in windy, cloudy periods.)

When well developed, the heat island maximizes over the most densely built-up parts of the city and decreases outward to a sharp gradient around the urban boundary. The maximum surface temperature differences between urban and rural areas usually occur at night, in fall or winter months, and during clear skies and light winds of anticyclonic weather conditions.

For those in other disciplines, I should explain that meteorologists use the term "surface" when referring to conditions in air 1 to 10 meters above ground level. The term "skin temperature" is used to denote conditions at the radiating surfaces, as seen by downward pointing radiometers.

Measurements by the Illinois State Water Survey, in METROMEX, show that the heat island at St. Louis is about what one would expect. Under clear to partly cloudly skies, it is best developed at 2000 and 0200 CDT, becomes broader but less intense at 0700 CDT, and is largely obscured by topographic factors at 1100 and 1500 CDT.

The diurnal variation of surface

temperature differs between urban and rural stations. A rural site warms more quickly, from a lower minimum, during the early part of the day, and cools more quickly during the afternoon and evening.

The diurnal pattern of skin temperatures of urban and rural terrain is different from that of air at low levels. Measurements by Dabberdt and Davis *(1974)*, using IR photometers on a low-flying airplane, showed that the maximum difference in skin temperatures at St. Louis occurred early in the afternoon on clear summer days but during night hours on winter days.

The intensities of heat islands increase with size of the city. Oke *(1973)* and Eagleman *(1974)* conclude that it varies with logarithm of population. Ludwig and Dabberdt *(1973)* propose a fourth root relationship. Landsberg *(1974)* shows that careful measurements will reveal local warming around even a few residential buildings.

Cloud cover and regional wind speed are important factors governing the development of heat islands. By altering radiation exchange between the surface and atmosphere, the effect of clouds is to reduce the heat island intensity *(Petersen 1969)*. Wind has the effect of ventilating a city and limiting the differences betwen urban and rural temperatures. Oke and Hannell *(1970)* summarize data on the critical wind speed above which a heat island is not usually detected, and show that the critical wind (U) was related to population (P) through the equation

$$U = 3.4 \log P - 11.6. \qquad [1]$$

In deducing causes for heat islands, it is useful to start by considering the thermal energy balance of the earth's surface, equation 2,

$$SW\downarrow + LW\downarrow + A = E + P + S + T + LW\uparrow. \qquad [2]$$

The energy sources for an area of the earth's surface consist of that portion of the solar radiation, SW↓, and atmospheric radiation, LW↓, which is absorbed by the surface, plus any anthropogenic heat released from terrain objects (A). These energy sources are balanced against the conversion of sensible energy into latent forms through evaporation and transpiration, E, and photosynthesis, P, the flux of sensible heat into the subsurface, S, and by flow of sensible heat into the atmosphere by diffusion, T, and IR radiation, LW↑.

Although all these terms contribute to the formation of heat islands, the most important appear to be energy used for evaporation and transpiration, flux of heat into the subsurface, and anthropogenic heat.

Evaporation is largely responsible for keeping rural temperatures lower on sunny days. Heat stored in urban surfaces during daytime, and returned to the air at night, is responsible for keeping urban areas warm long after radiation cooling dominates the rural scene.

The importance of anthropogenic heat has been debated; however, data compiled by Koenig and Bhumralker *(1974)* show that the urban-heat release in Manhattan exceeds the solar energy absorbed at the surface by a factor of 3.9. Even in an open park-filled city like Washington, D. C., the areal average heat release is equivalent to over 25 percent of the solar insolation.

STRUCTURE OF THE URBAN BOUNDARY LAYER

The heat island and surface roughness of urban areas combine to modify the atmospheric boundary layer from its upwind character. This modification is three-dimensional and varies with time of day and meteorological conditions. Observations of horizontal and vertical winds, temperatures, and water vapor, with sufficient accuracy and detail to delineate the urban boundary layer structure, are difficult to make and as yet inadequate to allow a complete description of it.

METROMEX studies show that the St. Louis heat island is measurable through the depth of the mixing layer. Temperature excesses of 1°K frequently are found as high as 800 m agl. During the summer days we find a mimimum in specific humidity with height-averaged deficits of 1 g kg^{-1} not unusual. These anomalous fields are displaced downward from the urban center by ambient winds. We sometimes find above the heat island a shallow cap of air slightly cooler than rural air at the same levels.

The top of the mixing layer at St. Louis domes up over the city in daytime, and morning rise-rates are faster than over rural areas. The mixing layer frequently undergoes a diurnal cycle as described in following paragraphs. Summer convective clouds appear earlier over the city and usually have higher bases than those over rural areas—up to 300 m in some cases.

Low level airflow at St. Louis is markedly perturbed by the city in light wind conditions. METROMEX data show that a frequent result is airflow convergence up to an average height of 1250 m with values as large as 0.5×10^{-4} sec^{-1} up to levels of 800 m agl. Measurements of atmospheric parameters and urban aerosol particles within and below cloud bases, plus results of tracer experiments, prove that air from the urban boundary layer feeds into and alters the properties of clouds. Measurements also show that clouds and rain are significant removal mechanisms for urban pollutants.

Numerical modelling suggests that the thermal excess at St. Louis is more important than surface roughness in raising the depth of the mixing layer, and under certain conditions, in displacing it downwind.

By combining these METROMEX observations with data from a number of other sources, we can outline the major features of the urban boundary layer during summer and fall convective weather conditions. Although this analysis is pointed particularly toward summer conditions at St. Louis, it should also serve as a point of departure for analyzing the boundary layer over other cities and during other seasons.

Before sunrise over rural areas one usually finds a deep radiation inversion. The inversion may be capped, or even replaced, by an isothermal layer if fog or heavy haze is present *(Pilie et al. 1975)*. Reduced vertical mixing across the inversion tends to decouple the winds from the surface resulting in light winds in the inversion and a sharp wind increase across it. Any shear-driven mixing layer will be quite thin.

Over both urban and rural areas, we may find considerable amounts of haze as a result of upward mixing (somewhere upstream) on previous days. Frequently the haze develops into layers along internal stable levels. The top of the haze may be very sharp, corresponding to a stable layer, and accompanied by a sharp drop in humidity. Other times the haze top will be ill-defined, merely thinning gradually with height.

Frequently, when the haze has a well-defined top, in early morning it will carry a thin stratus cloud layer formed through nocturnal radiational cooling from the haze. Meteorologists frequently call the entire haze layer, the "mixed layer" to differentiate it from the layer of active mixing, the "mixing layer" within it.

Over the city before sunrise, because of the heat island, any surface radiation inversion will be weak, perhaps limited to large air-drainage areas such as along river channels. The absence of a strong low-level inversion allows the wind to remain more tightly coupled to the surface, resulting in a turbulent mixing layer. At sunrise this layer may be 300 to 400 m thick and filled with smoke and haze; it may be capped with a weak elevated inversion. Above the surface mixing layer the haze and any stratus

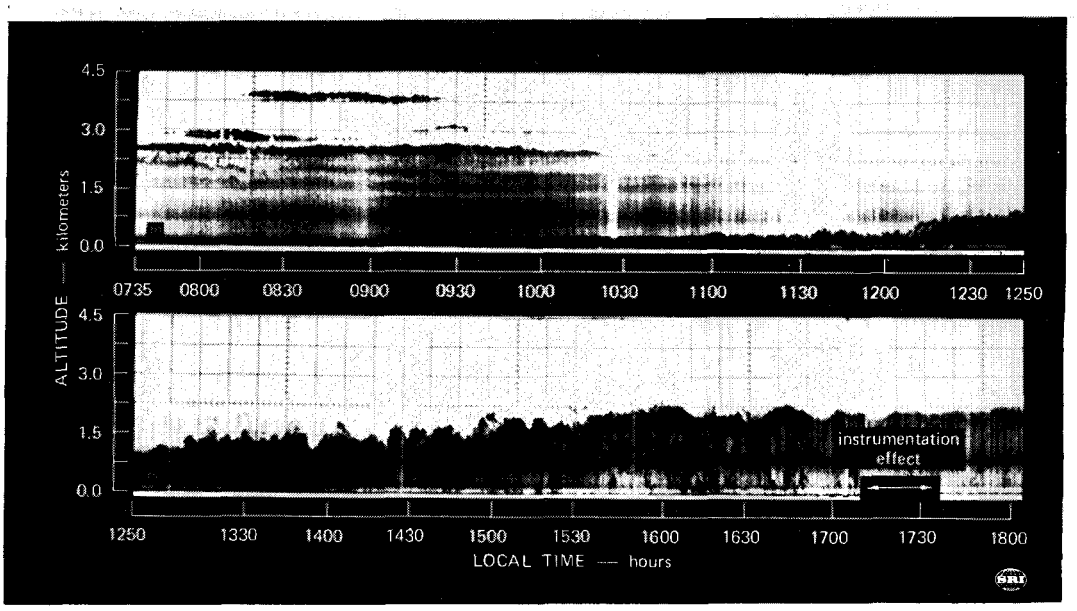


Figure 2.—Height-time cross section of the aerosol structure over St. Louis on 13 August 1971 as observed by Russell *et al. (1974)*.

cloud will be very similar to that over the rural areas.

After sunrise, both in urban and rural areas, any stratus present and the haze particles, will adsorb solar and IR surface radiation and begin to evaporate, improving visibility in the haze levels. These processes at St. Louis are seen clearly in time-height cross sections obtained by our colleagues from Stanford Research Institute with their Lidar (fig. 2, *Russell et al. 1974*).

In rural areas, the surface temperatures will rise rather quickly because the surface inversion limits the depth of initial heating. Dew may be present, in which case the initial temperature rise is delayed by diversion of energy into its evaporation. This in turn will provide additional vapor and tend to cause low-level visibility to decrease, or fog to thicken, for a brief interval in the manner discussed by Pilie *et al. (1975)*.

Within the city after sunrise, skin temperatures begin their climb almost immediately, aided by reduced amounts of dew. This results in a superadiabatic surface layer and initiates thermal convection. Uninhibited by a strong surface inversion, these "thermals" begin to thicken the mixing layer by enfolding air from above it, diluting the smoke and haze that has accumulated during the night. Because of the greater depth of air involved, the surface temperature will rise less rapidly than in the rural areas. As the mixing layer deepens and larger and larger thermals are involved, the top takes on a hummocky character seen so nicely in the Lidar data.

We are assisted in visualizing these dry thermal plumes through the work of Hall *et al. (1975)*, who used three covolume scanning acoustical sounders to study dry thermals near Boulder, Colorado. Their data show that individual thermals tended to rise nearly vertically and advect with the wind. They were more sharply defined on the upwind edge and less so on the downwind. (Perhaps due to mixing with the environment?) When the mixing layer was unstable to depths of 300 to 500 m, thermal updrafts were 2 mps and more over a broad mid-height range. Between the thermals were downdrafts with speeds of about one-half that of the updrafts. From double theodolite pilot-

balloon data at St. Louis, Ackerman *(1974)*, found similar values for dry vertical currents in the urban boundary layer. This "boiling" of the lower atmosphere is made visible on the Lidar by the presence of large quantities of aerosol particles (note fig. 2, 1130 to 1530 CDT).

After burnoff of the radiation inversion, the rural mixing layer develops in a similar manner but at a slower rate. According to Lidar data at St. Louis, the rural buildup lags that over the city by about 2 hours.

For several hours near mid-day, both urban and rural areas may have superadiabatic surface layers, above which the lapse rate is nearly adiabatic to the top of the mixing layer. In some instances, these superadiabatic layers are surprisingly deep. Using data from an instrumented TV tower in suburban Philadelphia, Davis and Newstein *(1968)* showed superadiabatic layers over 270 m deep on several days of pollution episodes in November 1966 and January 1967; presumably they are even deeper in summer.

On clear days the loss of energy by radiation and diffusion begins to exceed the incoming radiation by mid- to late afternoon, and surface temperatures start to decline. Typically, urban areas lag the rural by an hour or so in the onset of evening cooling. As surface temperatures decline, the source of energy for dry thermals is cut off and vertical mixing decreases.

On days when moisture conditions in the lower part of the boundary layer are adequate, clouds form at the tops of the strongest thermal plumes. When the mixing layer is limited by a strong stable layer, these clouds appear to sit in the top of the mixing layer with only their tops protruding above it (fig. 2). Under more favorable conditions, bulging cumuli may rise through the mixing layer to some elevated stable layer where their growth is arrested. Here they evaporate, leaving the pollutant materials they had ingested through the base as an elevated haze layer.

On days with very large cumulus clouds, the vertical structure of the boundary layer deviates from the orderly progression described above. For now the air motions induced by the cloud, (inflow into updrafts and outflow from downdrafts), begin to dominate the local wind field; evaporation of rain may destroy the heat island. In addition, cloud-shadowed and rain-cooled surfaces are less effective in feeding thermals.

The cool temperatures and high visibility of air that had descended in the downdraft and spread over the surface as a cool air dome are in marked contrast to the hot, hazy conditions before the storm.

In terms of air pollution, a major impact of large convective storms over urban areas is their ability to suck up very large volumes of surface-polluted air, scavenge many of the pollutants for deposition in the rain, and exhaust the remainder at heights up to the tropopause. Large convective storms over urban areas probably contribute appreciably to the Junge sulfate layer in the lower stratosphere.

Before leaving the subject of urban boundary layers, let's consider the results of numerical models of flow over heated islands. Estoque and Bhumralker *(1969)* show that for wind and stability conditions typical of summer at St. Louis, enhanced vertical mixing resulting from the heat island and surface roughness will bring down the higher momentum winds aloft, causing a gradual acceleration of the horizontal winds and slight subsidence over the heated surface. This study also shows that the main convective updraft will be displaced to the downwind edge of the island, very suggestive of the downwind thermal plumes observed by Clarke *(1969)* at Cincinnati. If the models can be applied to conditions over urban areas, subsidence could help explain the

moisture deficits observed over St. Louis. Moreover, the downwind displacement of the convection field fits with observed rain excesses on the downwind side of the city.

URBAN EFFECTS UPON CLOUDS AND HAZE

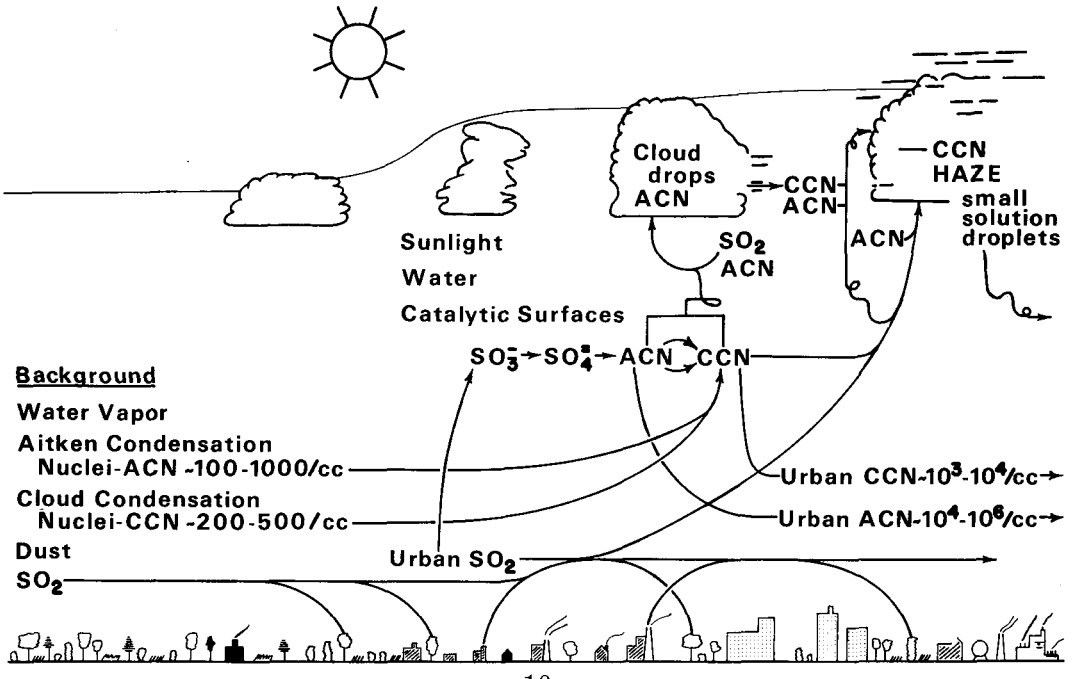
Cities such as St. Louis have a marked effect upon the sizes and concentrations of drops in clouds that ingest the urban air. This effect results from the large numbers of cloud condensation nuclei, CCN, that form within the urban plume. The processes whereby this takes place are outlined in figure 3.

In the pristine atmosphere, far removed from man-made influences, CCN are thought to be submicron particles of ammonium sulfate and sea salt. The sulfate appears to come from biologically derived sulfur gases such as H_2S. In urban atmospheres large quantities of SO_2 are released from fossil fuel combustion and by certain industrial and mining-smelting activities. Much of this sulfur dioxide quickly mixes to the surface where it is absorbed by plants in the first few hours downwind (at least in summer). METROMEX studies give a half-residence time of 4.5 hours for SO_2 released from St. Louis in summer.

Some small fraction of the SO_2 undergoes gas-to-particle conversions to give small particles of sulfuric acid and sulfates. Chemists still are studying the various reactions involved in this process, but there seems to be general agreement that the transformation is most rapid in the presence of sunlight, water, and trace catalytic surfaces. Sulfur dioxide is not the only gas that undergoes conversions to particles. Oxides of nitrogen from automobile exhaust, and other urban effluents, may undergo similar transformations.

Particles formed by gas-to-particle conversions quickly reach sizes of 5×10^{-6} cm and are called Aitken particles or Aitken condensation nuclei (ACN) since they are measured in de-

Figure 3.—Schematic outline of processes responsible for the production of urban nuclei and urban aerosols.



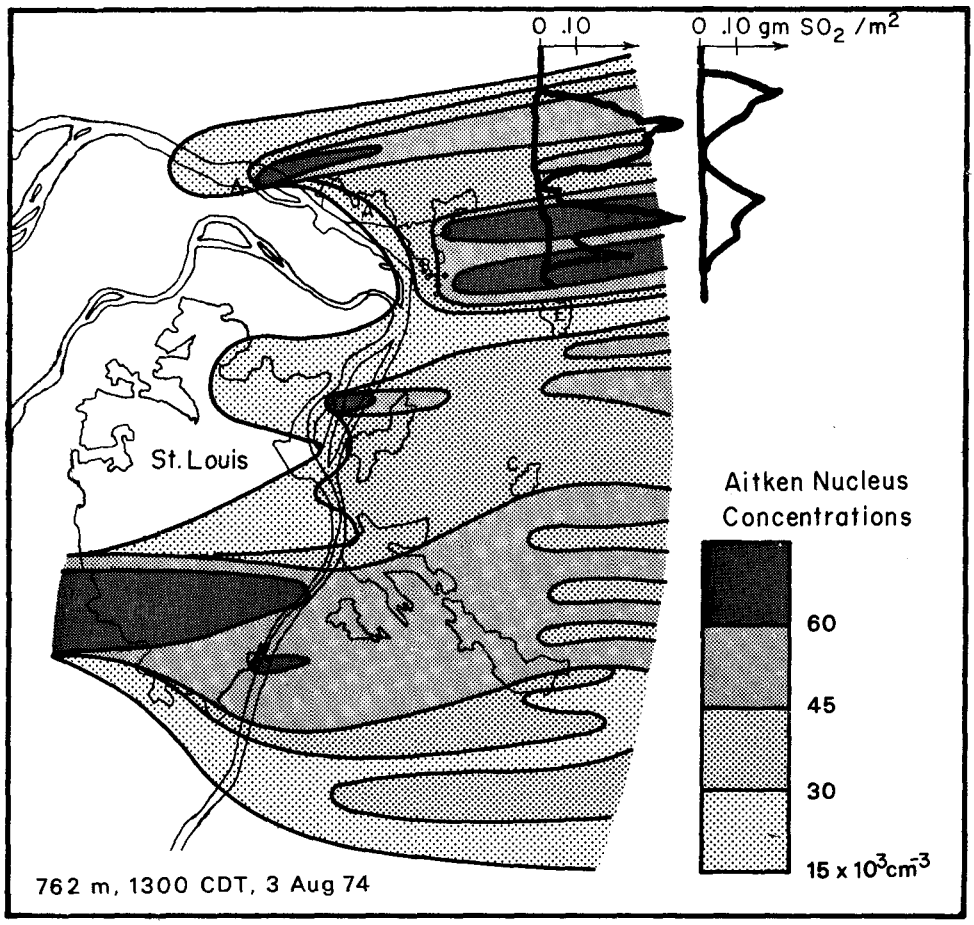


Figure 4.—Aitken nuclei plumes in the urban boundary layer over St. Louis on 3 August 1974, with superimposed plumes of SO_2 as measured by Vaughan *et al. (1975)*. The plumes in the upper right show the SO_2 overburden (gm/m^2) above two north-south highways.

vices that cause them to nucleate droplets through supersaturations of several fold.

The concentrations of ACN in clean oceanic air, or over land well above the influences of man's activities, usually are a few hundred cm^{-3}. In the rural boundary layer upwind of St. Louis, summer concentrations are of order 10^3 cm^{-3}. In the urban plume typical values are $10^4 - 10^5$ cm^{-3}. Estimated source strengths of industrial areas are about 1-3 x 10^6 cm^{-2} sec^{-1}.

Aitken particles are too small to directly affect clouds, but they serve as excellent tracers of the urban plume. Using data from our instrumented airplane, we have prepared maps showing ACN plumes for selected clear-sky situations. One such is shown in figure 4. These maps show several Aitken particle plumes arising from industrial areas and large power stations, the large SO_2 emitters in data compiled by EPA. Presumably highway traffic also is a contributor to urban ACN, but our data in St. Louis do not readily resolve such disperse sources. While we were obtaining these data, other scientists were measuring the vertically integrated SO_2 along two highways over which the airplane was flying *(Vaughan et al. 1975)*. Their results are also shown in the upper right quadrant of figure 4. It is

clear that the ACN plumes coincide exactly with total SO_2 plumes.

Maps such as these show that the urban plume is a composite of plumes from a number of intense point sources superimposed upon a background from the city. Our data show that in the neutrally buoyant boundary layer, the ACN plumes quickly mix vertically through the depth of the mixing layer and spread horizontally about 10 degrees.

Once formed, Aitken particles continue to grow by further adsorption and oxidation of SO_2, and by coagulation among themselves. New ones keep forming and others are destroyed by coagulation and by interception by haze and cloud particles. The latter process is relatively slow since our measurements inside urban clouds show ACN concentrations exceeding nearby clear air values several fold, at least up to 3 km above cloud base.

The larger the size of a submicron soluble particle, the lower the supersaturation required for it to nucleate and begin growth into a cloud drop. The supersaturation in the bases of many clouds is approximately 0.5 percent (R.H. = 100.5 percent). Particles capable of nucleating in this range of supersaturation are called cloud condensation nuclei (CCN).

Our measurements at St. Louis show that the city is a source for CCN, in both winter and summer, with source strengths of about 10^4 cm^{-2} sec^{-1}. This is equivalent to a volume source of about 0.1 particle sec^{-1} cm^{-3} of urban plume.

One of the key issues as to whether urban CCN can be small sulfate particles concerns the reaction rates of SO_2 conversion into SO_4. Measurements of sulfates in rain over and immediately downwind of St. Louis account for 10 to 20 percent of the SO_2 emission, according to METROMEX measurements. If one assumes that all urban CCN are pure sulfate formed from SO_2, the amount required is substantially less than that observed. Thus it appears that conversion of SO_2 can account for urban CCN, at least in St. Louis.

Ingestion of anthropogenic CCN into the bases of urban clouds results in drop concentrations up to twice that of nearby rural clouds. The sizes of urban cloud drops are correspondingly smaller and the spectra more peaked. A typical example of urban and rural cloud drop spectra is given in figure 5. These observations are in accord with theories relating drop spectra to CCN and updraft speeds *(Mordy 1959, Warner 1969, Fitzgerald 1972)*.

HAZE FORMATION

The mechanism of urban CCN production and nucleation in urban clouds appears to be closely related to one of the most serious of all air-pollution problems—viz., the formation of haze and low visibility during periods of stagnant anticyclonic circulation. During such periods, we find that the minimum visiblity is in the upper part of the mixing layer where there is a scattered to broken layer of shallow cumulus clouds. These clouds evaporate without raining. Between the clouds, and below their bases, are haze particles with modal sizes of several microns, and concentrations of order 1 cm^{-3} of particles up to 15 microns diameter. To be stable at the slight subsaturations involved, these haze particles are most likely small solution drops.

We believe that these particles form by repeated cycling of Aitken particles, SO_2, and CCN through the short-lived clouds (fig. 3). With each nucleation and growth into a droplet, the CCN grow larger. The end product is a large number of large solution particles. Easter and Hobbs *(1974)* discuss the chemistry of this process when operating in shallow wave clouds.

Once created, these solution drops can survive vertical mixing through the depth of the mixed layer and advection over great distances from the SO_2

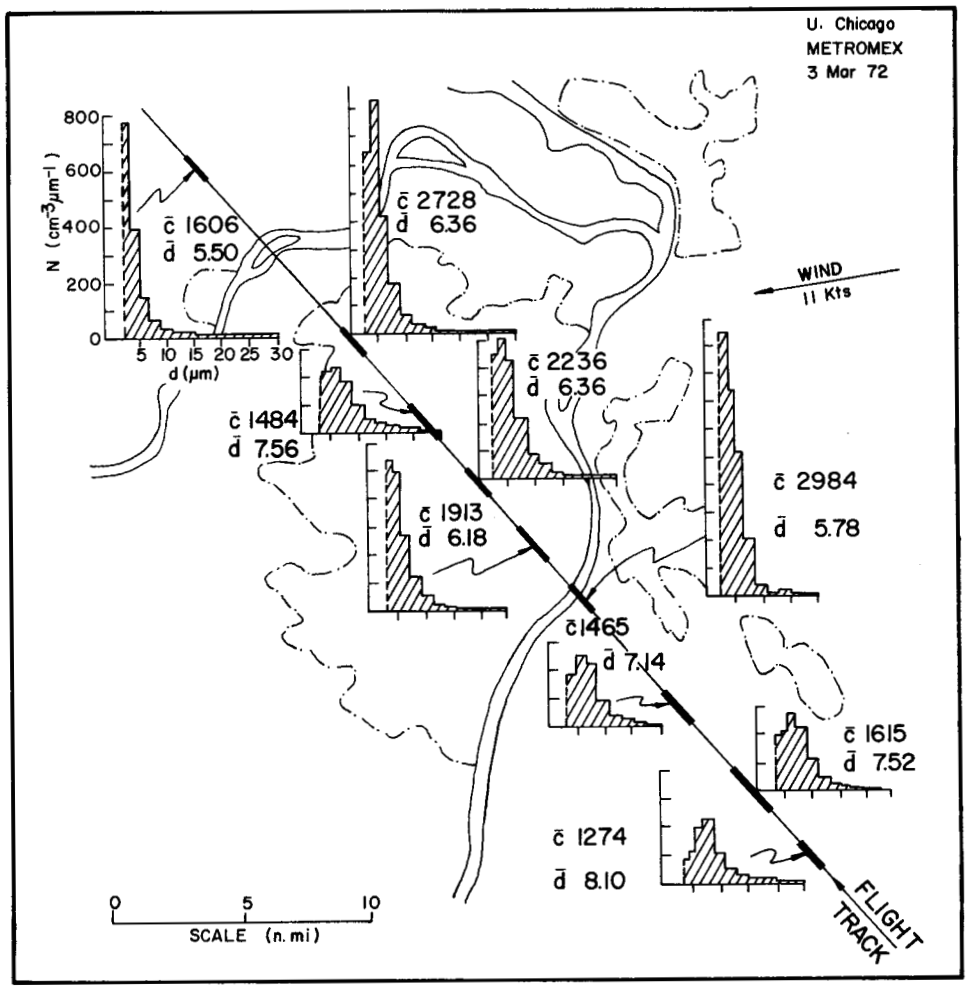


Figure 5.—An example of the effect of urban-CCN on size spectra of drops in clouds. Note the great difference between rural spectra (southeast end of the track) and those downwind of industrial areas and large power stations.

sources. In a sense these drops constitute a disperse cloud which in severe pollution episodes may become thick enough to obscure the sun.

URBAN EFFECTS UPON PRECIPITATION

The meteorology of urban effects upon precipitation is poorly understood compared with that of the urban heat island and the changes in cloud microstructure and visibility resulting from the growth of urban CCN. The issues are at least an order of magnitude more complex, involving interacting cloud dynamical and cloud microphysical processes, both of which are poorly understood and dependent upon conditions of the atmosphere below and around the clouds.

Urban rainfall effects have been studied in two ways: by statistical analysis of precipitation elements observed around cities and by studying the urban-rural difference of cloud dynamical and cloud physics parameters known *a priori* as related to natural precipitation.

Viewed by one who has not been involved in the statistical treatment of

observed rain around cities, this approach seems to be troubled by questions of the accuracy and representativeness of historical data and by the difficulty in separating urban effects from local topographic effects. It is well established that low hills (100 to 200 m) can produce local precipitation anomalies comparable to that attributed to urban effects (e.g., *Jones et al. 1974, Bergeron 1968*). Every city is uniquely integrated into its local topography, and there is no statistical device that will unambiguously separate natural topographic effects from those due to man's alteration of the topography by buildings, parking lots, etc. Weekend vs. weekday partitioning of the data and stratifying by wind direction can help reduce, but not eliminate, this problem.

The belief that there is more rain in or near cities than would have occurred at the same location had the city not been built seems to rest mainly upon two facts: (1) local excesses have been observed at a number of (though not all) cities located in a variety of topographic situations; and (2) studies of historical data have shown increasing rain anomalies at some cities as they have grown and become industrialized.

METROMEX has been involved in statistical analyses of rain data, but it also has been deeply involved in measuring physical variables associated with rain at St. Louis in an effort to understand the physics of urban rainfall. According to studies from the Illinois State Water Survey, the largest urban effects at St. Louis are associated with squall lines and squall zones, conditions favorable for natural development of large clouds and moderate to heavy rain. Thus we are faced with the task of working with large clouds whose mere size and complexity make direct observations difficult.

A number of hypotheses have been advanced for physical mechanisms whereby cities might induce local rain excesses. These tend to divide into two groups: those stressing dynamical effects arising from the heat island and surface roughness, and those involving microphysical effects associated with urban derived nuclei, aerosol particles, etc. In either case, one assumes that the urban effect operates by altering natural precipitation mechanisms in some manner.

There are two mechanisms of natural precipitation *(Byers 1965)*. The first recognized and best known is one involving ice particles growing by vapor diffusion in a supercooled cloud; i.e., a cloud of liquid droplets which have cooled below 0°C without freezing. Ice particles are initiated by ice-forming nuclei (IFN). In general, IFN are not the same particles as CCN.

Although data are conflicting, so far it appears that St. Louis is not a significant source of IFN. In fact, it may act to poison natural IFN, especially in the winter months.

The second mechanism of natural rain formation involves collision and coalescence between cloud drops. Many collisions are required because a single rain drop has the mass of about one million cloud drops. Initiation of this mechanism is favored by a broad spectrum of cloud drops such that drops larger than about 40 microns diameter can overtake and coalesce with smaller ones. This mechanism does not require ice particles and can operate equally effectively in clouds either warmer or colder than freezing.

It has been known for some time that coalescence is the dominant mechanism for initial development of rain in cumulus clouds in the Midwest in summer.

Theory says that the narrow drop spectra in urban clouds should delay initiation of the coalescence mechanism. But in fact, the RHI radar shows that coalescence is speeded up, not delayed, in summer clouds over St. Louis. It appears that these clouds also develop a few very large cloud drops, too large to relate to the CCN spectra as usually

measured. These drops appear as a "large drop tail" on spectra measured in clouds downwind of the city. We presume that these large drops are associated with particulate pollution from the city.

When developing precipitation in a cloud becomes intense enough to be detected by radar we have what is called a radar "First Echo" (FE). In the St. Louis study we find that FE's are warmer than 0°C, hence are coalescence induced. Also, on average, urban FE are slightly lower and warmer than those of rural areas.

The Greenville 3-cm radar shows that the frequency of formation of FE is not uniform over the radar area, with a region of maximum occurring over and downwind of St. Louis.

At the time cumulus clouds produce 3-cm FE's, they have tops barely reaching the freezing level. Unless these clouds continue to grow, the rain they produce will be rather modest.

Let's turn to some of the Illinois State Water Survey measurements of summer rain at St. Louis. They show that the rain pattern for the first three summers of METROMEX was a north-south ridge of rain excesses about 10 miles east of the Mississippi River, and a trough of low rain amounts across the western suburbs. The greatest rain totals were around Edwardsville, Illinois, about 18 miles northeast of the famous St. Louis riverfront Arch. The average rain amount in the ridge is about 1.36 that of the trough.

Over 60 percent of the rain in the Edwardsville area occurred in storms depositing an inch or more. In addition, Edwardsville had substantially more thunderstorms and hail than were observed west of the Mississippi River. Obviously the rain excess at Edwardsville came from clouds much larger than those producing FE's.

When rain periods were stratified by pre-storm wind direction, the downwind quadrant had the larger amounts of rain.

The fraction of each station's total rain that fell during the hours of strongest convection, 1500-1800 CDT, shows a strong maximum centered directly over the city.

Time and space does not permit enumerating the many other observations about clouds and rain which are available on METROMEX. These may be obtained from the Project Principal Investigators.

The most thoroughly developed hypothesis, thus far, to explain the excess in summer rain east of St. Louis, is that of Boatman and Auer *(1974)*. Measurements made by the University of Wyoming group showed that some thunderstorms moving into the city picked up drier and warmer urban air (lower θ_e), which caused the updraft to weaken. University of Chicago radar showed decreases in the heights of the echo tops shortly thereafter. Boatman and Auer argue that the decreasing strength of the updrafts would accelerate the release of suspended precipitation.

This hypothesis is logical and fits observations. It may indeed account for some of the rain excesses over the city. However, it is hard to see how it relates to the observation of increased thunderstorms and hail east of the city since these storms would presumably be declining in intensity as they cross the city.

A second hypothesis that seems reasonable but is less well investigated says that the low-level instability associated with the heat island, plus any action of the city to focus and localize the release of regional instability, might be sufficient to allow the development of large clouds in marginal situations. For example, it has been observed that radar echoes near St. Louis have a bimodal top-height distribution. Large numbers of echoes have tops around the freezing level as a result of mid-level stability on convective days. If the additional buoy-

ancy at cloud base permits some of these clouds to penetrate the stable layer and reach glaciation levels of −10 to −20°C, the heat of glaciation may then provide significantly additional growth, and more rain. It may also be that glaciation is accelerated in urban clouds through microphysical processes associated with urban derived nuclei; however, this possibility has not been demonstrated.

At this time, and stressing again that Project METROMEX is still in progress, it seems to me most likely that any urban effects upon rainfall are associated with cloud dynamical effects associated with the heat island and surface roughness. Cloud microphysical effects, so obviously important in altering cloud-base microstructure and in the development of haze, are probably of less importance in explaining rain anomalies unless there are feedback processes that we have not yet explored.

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Acknowledgments.—The author is deeply indebted to the many Principal Investigators of Project METROMEX whose findings have contributed to this paper. Project METROMEX is supported by the National Science Foundation (RANN) Grants AEN72-03399-A03, AEN73-07882, AEN73-07796, AEN73-07881, AEN76-00898; NSF (Engineering) Grant GK-38329; Energy Research and Development Administration Grant 1199, and Division of Biological and Environmental Research; Environmental Protection Agency Grant R-800875; and the State of Illinois, State Water Survey.

Mesoscale Features of Urban Rainfall Enhancement

by F. A. HUFF, *Illinois State Water Survey, Urbana, Ill. 61801.*

ABSTRACT. Analyses of data from the first 4 years of a 5-year research project at St. Louis indicate a substantial enhancement of summer rainfall downwind of the urban-industrial complex. This anomaly appears to be caused primarily by the intensification of naturally occurring storm systems through the addition of heat and raindrop nuclei from the urban area. Most of the enhancement is associated with organized storm systems and is most pronounced during and after the period of maximum diurnal heating.

SINCE 1971, AN EXTENSIVE field and analysis program (METROMEX) has been under way in the St. Louis region to investigate the causes and effects of urban enhancement of precipitation in and downwind of large urban-industrial complexes *(Changnon et al. 1971)*. Huff and Changnon *(1972)*, in a study of eight major cities in the United States, found that the urban environment tends to enhance total precipitation, heavy rainstorms, and severe weather (hail, thunderstorms) in the vicinity.

The St. Louis program involves various types of surface and low-level atmospheric measurements of meteorological parameters. However, this paper is concerned only with findings for the summers of 1971-74 that have been obtained from analyses of data from a dense network of 225 recording rain gages in a circular area of 5,200 km^2 (fig. 1) and a 10-cm PPI radar (FPS-18). These two data sources have provided much information on the differential time and space characteristics of summer precipitation exposed to (1) the urban environment, (2) regional topographical influences, and (3) flat rural areas that serve as a control in evaluating urban and topographical effects on the regional rainfall distribution. Summer is emphasized because the earlier climatic studies *(Huff and Changnon 1972)* showed that the urban effect is most pronounced at that time in the Midwest.

In the METROMEX analyses, four potential sources of localized weather effects were evaluated: the major urban-industrial area of St. Louis, a major industrial area located 10 to 15 km north of St. Louis at Alton-Wood River, and two orographic features (fig. 1). The first of these topographic features is the Ozark Hills, which begin a few kilometers southwest of St. Louis, and the second is the bottomlands of the Missouri River, northwest of St. Louis and west of Alton-Wood River. The roughness of the hills can accelerate both the development and intensification of convective clouds, and the bottomlands are a heat-moisture source conducive to development of convective clouds.

SUMMER RAINFALL PATTERN

In the Edwardsville area the total summer rainfall for 1971-74 (fig. 1) indicates a peak that is frequently downwind of both urban-industrial areas, since westerly winds prevail. The Edwardsville high (120 cm) represents a 30 percent positive deviation from the network mean of 91.3 cm, or more than two standard deviations above the mean. The location of this peak and its large departure from the network mean are considered strong supporting evidence of an urban enhancement of precipitation. The lightest rainfall in the

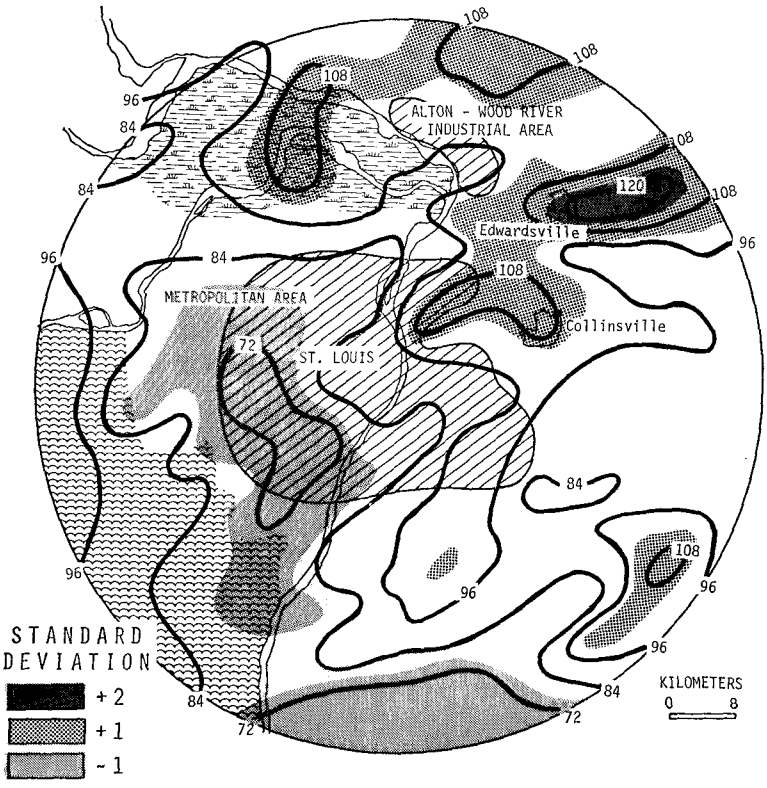


Figure 1.—Total summer rainfall, 1971-74.

four-summer period occurred west and southwest of the major industrial area, which is located along the east of the river. The low region is usually upwind of the industrial region. Thus, the four-summer pattern (fig. 1) shows highs in regions most frequently downwind of the major urban-industrial areas (northeast, east, and southeast of the river) and lows in areas upwind of the urban-industrial complexes.

SYNOPTIC WEATHER RELATIONS

An important consideration in evaluating the causes of urban rain enhancement is the distribution of the precipitation by synopic weather types. In the METROMEX research, efforts have been made to determine what weather processes are active in all rain periods, with special emphasis on the early stages of each rain period, when the urban heat island should exert its maximum effect. In so doing, storms have been classified into five basic synoptic types *(Vogel and Huff 1975)*. These include fronts (cold, warm, stationary), squall lines or squall areas, prefrontal and postfrontal rains, low-pressure center passages, and nonfrontal air-mass storms.

Results to date indicate that more than 75 percent of the summer rainfall in the St. Louis region is associated with organized squall lines and squall areas. These and cold fronts have accounted for nearly 90 percent of the total rainfall on the rain-gage network. Although air-mass storms have accounted for more than one-third of the summer storm occurrences, they produced less than 3 percent of the total network rainfall in 1971-73. This has led to the tentative conclusion that the more active and intense the synoptic situation, the greater are the chances that the city

will effectively enhance the precipitation. The air-mass storms, which are unorganized, spatially scattered and usually short-lived, have contributed very little to the rainfall highs easterly of the urban-industrial complexes (fig. 1.)

WIND-RAIN RELATIONSHIPS

Another useful analysis in evaluating the urban effect is to determine the association between surface or low-level winds before rainstorms and the pattern of the resulting rainfall. Both storm movement and the ingestion of heat and particulates (source of rain drops nuclei) into storm systems are related to the low-level wind field. Therefore surface winds have been grouped according to the quadrant from which they blow and averaged for 1 to 3 hours before rainfall, depending upon wind speed. With an active urban enhancement mechanism, the rainfall would be expected to maximize in the quadrant downwind of the city with a given wind movement.

Results to date indicate that, in general, the expected distribution occurs. For example, in 1973 (table 1) the above hypothesis held for all wind movements. That is, with winds blowing from the northeast quadrant (0°-89°) the maximum rainfall with these surface winds (1.40 cm) was in the southwest quadrant. Similarly, the heaviest seasonal rainfall with southeast winds was in the northwest quadrant (15.00 cm), the maximum with southwest winds in the northeast quadrant, and the peak with northwest winds in the southeast quadrant. That is, in each case the highest percentage in each quadrant occurred when the prevailing wind prior to rainfall was blowing across the urban-industrial area. The wind-rainfall relations provide additional evidence of the reality of the observed tendency for the urban environment to enhance the naturally-occurring rainfall downwind of the city.

DIURNAL DISTRIBUTION OF THE URBAN EFFECT

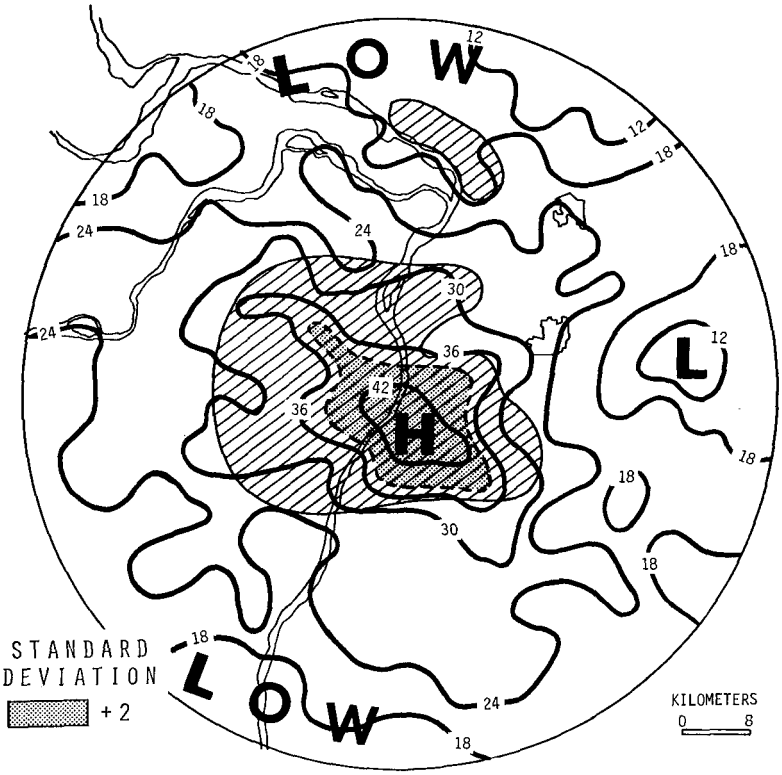
It was hypothesized that the urban effect would maximize diurnally during and immediately after the period of maximum solar heating. At that time, the urban heat discharge combined with the solar heating would tend to produce maximum destabilization in the lower layers of the atmosphere. Then convective growth or development would be favored by the increased thermodynamic instability and/or transferal of raindrop nuclei from stack discharges to cloud base, where they could stimulate the cloud-precipitation processes.

Analyses showed that rainfall tended to maximize over the immediate urban area (fig. 2) in the late afternoon. From 1500 to 1800 CDT, several rain gages in the southeastern part of St. Louis recorded more than 40 percent of their total rainfall for the three-summer period 1971-73. A considerable portion of the urban area (fig. 2) had percentages that exceeded two standard deviations above the network mean of 24

Table 1.—Relation between prevailing surface wind direction before start of rain and network rainfall during summer 1973

Prevailing wind direction	Mean rainfall (cm) for given network quadrant			
	NE	SE	SW	NW
N-E	0.15	0.51	1.40	0.69
E-S	12.20	12.97	12.50	15.00
S-W	11.58	10.00	3.08	2.47
W-N	.25	1.02	.25	.15

Figure 2.—Rainfall pattern for 1500-1800 CDT, 1971-73.



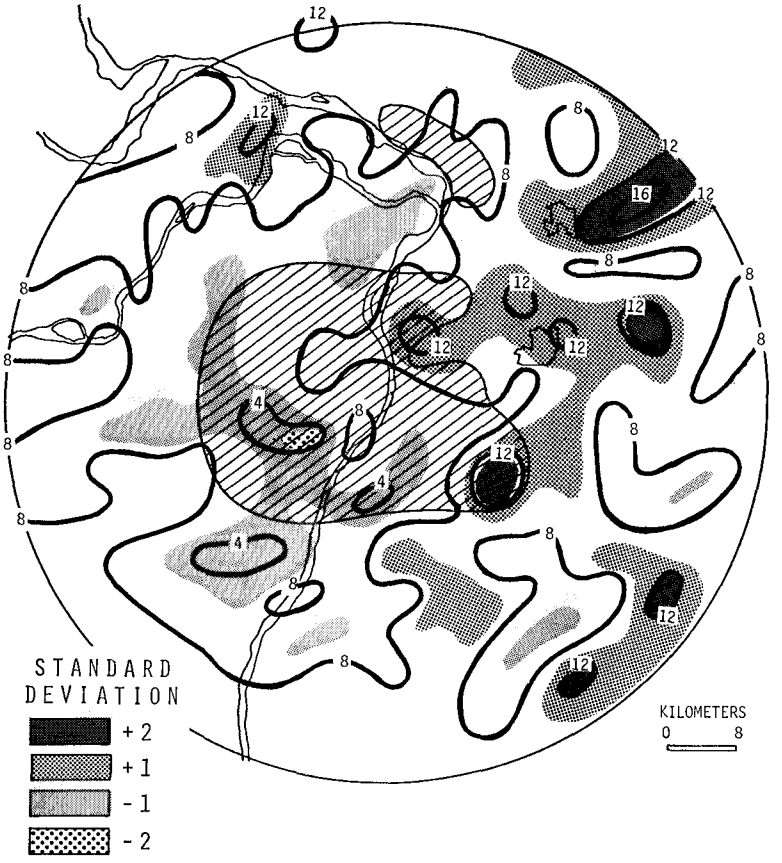
percent of the total rainfall for the three summers. During the following three hours, 1800-2100, the high in the diurnal pattern shifted eastward, as would be expected with raincell initiations in the urban area leading to raincell mergers and intensification of rainfall easterly of the urban-industrial areas. The later high was centered approximately 20 km east of the center at 1500-1800 (fig. 2) and had amounts exceeding two standard deviations above the network mean. Thus the diurnal patterns provide further evidence of an urban-induced enhancement of the natural rainfall downwind of the urban-industrial area.

URBAN EFFECTS ON HEAVY RAINFALL

Another finding from the eight-city climatic study *(Huff and Changnon 1972)* was that the urban effect was most active on days when atmospheric conditions were favorable for storm development from natural processes, and this resulted in a substantial increase in the number of heavy rainstorms downwind of large urban-industrial areas. The earlier finding has been supported by the METROMEX studies, in which the frequency of storm rainfalls of 25-mm or more and their contribution to the total seasonal rainfall have been determined. These storms are of an intensity to be of importance to the hydrologist concerned with the design and operation of urban storm and sanitary sewer systems.

Analyses of the frequency of 25-mm rainfalls at each rain gage during the four summers, 1971-1974, showed a maximum northeast of St. Louis in the Edwardsville area (fig. 3) where the total seasonal rainfall was highest (fig. 1). The low region of heavy rain occurrences was west and southwest of the

Figure 3.—Frequency of 25-mm storm rainfalls, 1971-74.



river (fig. 3) in the same region as the four-season rainfall low. The maxima of 14 to 16 occurrences in the Edwardsville high (fig. 3) were more than two standard deviations above the network mean of eight storms. Rainfall in these storms accounted for over 50 percent of the total rainfall in the Edwardsville high for the 1971-1974 summers; this emphasizes the importance of the heavy storms in defining the general rainfall pattern and controlling the location of high and low centers in the network pattern.

Our studies to date indicate that the maximization of heavy rainstorms in the Edwardsville region occurs from the enhancement of natural storm systems, particularly squall and cold-front systems, as they move across the St. Louis or Alton-Wood River areas. The urban environment acts to intensify existing raincells and to initiate new raincells within ongoing storm systems. This results frequently in maximum rain outputs near Edwardsville, which lies a few km east-southeast of Alton-Wood River and northeast of St. Louis.

A number of case studies have shown that quasistationary mesosystems, maintained by mergers with urban related convective cells, are a common cause of severe rainstorms of hydrologic significance in the urban region *(Vogel and Huff 1975)*. Mergers are frequently associated with storm intensification, and these are favored in the urban region where the environment stimulates new raincell formations and growth of existing convective entities. Other findings from the METROMEX studies show that raincell initiations are frequently

associated with "hot spots" in the experimental area, and these occur more frequently within the urban region than in the surrounding rural regions. From aircraft measurements, there are also indications that large amounts of condensation nuclei of urban origin are commonly ingested into cloud systems in the vicinity, and this provides another potential mechanism for initiating rainfall and intensifying ongoing storm systems. In general, analyses to date indicate that excessive heat output from the urban region (a destabilizing force), and raindrop nuclei ingestion from the urban-industrial stack outputs, are probably the major causes of urban rainfall enhancement.

RAINCELL ANALYSES

A primary method of evaluating the urban effect in METROMEX studies has been through comparison of urban-affected and rural (non-affected) raincells. Only those cells that spent their entire life on the network (complete cells) are used. Comparisons have been made for various stratifications of the data, but in this paper I will discuss only analyses of heavy raincells that are of primary concern to the urban hydrologist. For this purpose, the 300 cells with the heaviest mean rainfall were separated from the 2,688 complete cells sampled in the 1971-73 summers. This included all cells with mean rainfall of 6 mm or more. A raincell is defined as a closed isohyetal entity within the overall enveloping isohyet of a rainstorm system; that is, it defines an isolated area of significantly greater intensity than the system enveloping isohyet, and must last more than 5 minutes to qualify as a cell *(Schickedanz 1972)*.

Comparison of the water yield (rainfall volume) from the heavy cells with all 2,688 cells showed that the 300 cells (11 percent of total) accounted for 63 percent of the total water yield. Similarly, the heaviest 100 cells (4 percent of total) produced 40 percent of the water output by all 2,688 cells, and the 50 heaviest cells (2 percent) accounted for 28 percent of the 2,688-cell rainfall. The weight that these cells exert in determining the network rainfall pattern and the magnitude of any urban effect is obvious from the above calculations.

A cell was considered to be potentially urban-effected if it developed over or passed through either of the two major urban-industrial areas. Of the 300 heavy cells, 118 were classified as urban-effected and 134 were included in the rural (no-effect) group. The remainder fell into the topographic-effected group. A comparison of percentage differences between the water yield of these two groups showed that the urban cells had a median output of $1.05 \times 10^6 m^3$, which was 55 percent greater than the rural cell median (table 2). The difference was 97 percent or more for the heaviest 5 percent of the cells and was 29 percent or greater when 95 percent were included. The comparison of water outputs associated with the urban and rural cells (table 2) provides further evidence

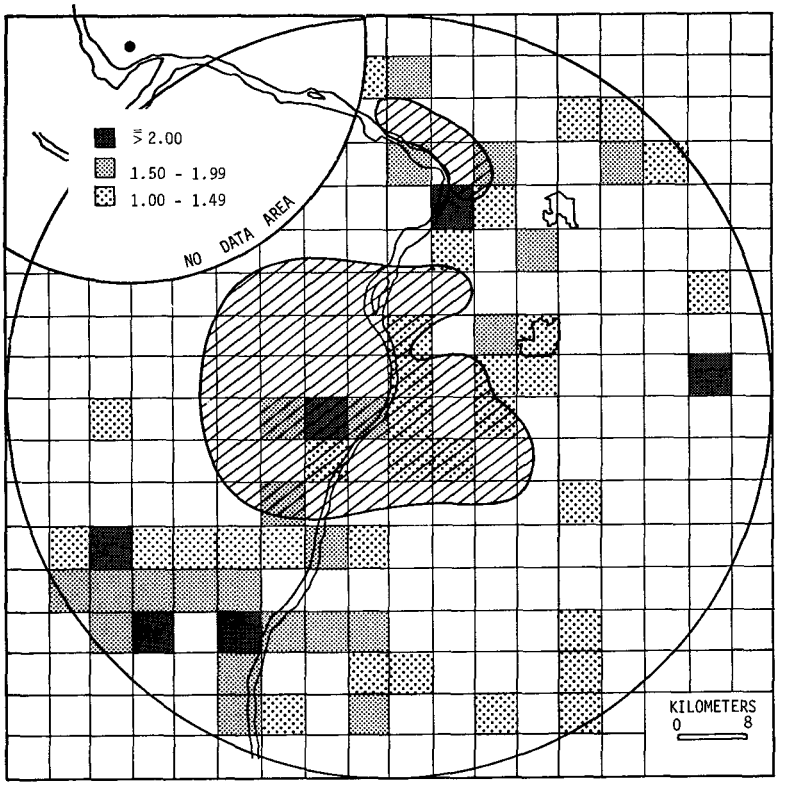
Table 2.—Comparison of water yield between urban-effect (U) and no-effect (C) raincells among 300 heaviest cells in 1971-73

Cumulative percentage of raincells	Urban-effect volume (m^3)	U - C (m^3)	Percent difference
5	4.75×10^6	2.32×10^6	97
25	1.99×10^6	8.43×10^5	73
50	1.05×10^6	3.70×10^5	55
75	5.83×10^5	1.82×10^5	45
95	2.47×10^5	5.56×10^4	29

Table 3.—Comparison of percentage difference between urban-effect and no-effect rainfall parameters in 1971-1973 heavy raincells

Cumulative percentage of raincells	Percentage difference equalled or exceeded			
	Mean rainfall	Area	Path length	Duration
5	20	72	72	42
25	11	51	56	20
50	11	35	45	10
75	10	32	29	14
95	10	25	17	11

Figure 4.—Number of radar echo initiations per 25 mm of rainfall.



of the urban effect and its observed tendency to increase with increasing rainfall yield from natural causes. Statistical tests (u-test and t-test) showed the urban-rural differences to be significant at the 1 percent probability level.

Comparison of urban-rural raincell differences for various rainfall parameters showed the maximum difference associated with rainfall volume that integrates the effects of cell area, duration, intensity, and path length. However, other parameters did show larger values for the urban cells (table 3). For example, median percentage differences were 45, 35, 11, and 10 percent respectively for cell path length, area, mean rainfall, and duration (table 3) compared with 55 percent for rainfall vol-

ume (table 2). This consistency of positive differences between cell parameters adds to proof of the urban effect.

RADAR MEASUREMENTS OF URBAN EFFECT

Analyses were made of radar echo observations from 27 storms sampled with the 10-cm FPS-18 radar in 1972-74. Major emphasis was placed on preferred areas of echo initiation and echo mergers in the METROMEX network. Initiation counts were based upon the number per 23 km^2 (9 mi^2) and merger counts on the frequency per 92 km^2 (36 mi^2). Results of these analyses indicated a strong trend for echo initiations (rain entities) to occur most frequently in and downwind of the urban-industrial areas and in the Ozark foothills (fig. 4). The most frequent region of occurrence was in the vicinity of oil refineries at Wood River, where the normalized frequency (number/25-mm of rainfall) was 50 percent greater than for any other unit area in the network.

Raincell and radar echo mergers are frequently associated with intensification of ongoing storm rainfall. Therefore the radar data were examined for the distribution of echo mergers in the 27-storm sample. Results showed the most frequent area of mergers near the eastern and southeastern boundaries of the urban area of St. Louis, and a secondary maximum appeared in and downwind of the Ozark Hills, as well as downwind of the urban area. Thus, the radar analyses add support to validation of the urban enhancement mechanism by exhibiting a source of above-normal frequency of raincell development and intensification in the urban-industrial regions. The radar analyses also showed that the foothills are likely a region of topographic effect on convective development and rainstorm enhancement.

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Acknowledgment.—This research was carried out under the general direction of S. A. Changnon, Jr., head, Atmospheric Sciences Section, and was partially supported by the National Science Foundation under Grant GI-38317.

The Urban Moisture Climate

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ABSTRACT.—Data collected on 26 July 1974 as a part of project METROMEX in St. Louis show the three-dimensional structure of the urban moisture field. Mesoscale dry regions at the urban surface, corresponding to large residential and light industrial land-use characterization, were responsible for a reduction in specific humidity in the urban mixing layer. Anthropogenic sources and sinks of water vapor were estimated and found to be insignificant for summer daytime mesoscale influences on the atmospheric water balance of the urban area. The effects of reduced moisture in the urban area are directly related to the urban heat island, visibility, fog, precipitation, and human comfort in our cities.

HUMAN LIFE PATTERNS have changed radically in the last century with the increasing migration from rural to urban areas. The increased magnitude of climatic anomalies accompanying urban-industrial expansion are well documented by the urban heat island and are further evident in the effects on visibility, fog, moisture, and precipitation. These factors are important to human comfort, land-use planning, and engineering considerations.

The moisture budget appears to be a key contributor to urban climate anomalies. Seasonal surface-moisture anomalies have been noted in large urban areas. The greatest urban-rural humidity differences are during summer afternoons when the urban dry island is greatest in magnitude. Summer nighttime differences in urban-rural absolute humidity patterns suggest that the city is drier when the nocturnal heat island is strongest. Wintertime studies, however, show that the urban area is more moist than its rural counterpart. Intensification of the urban heat island has been directly related to less absolute moisture *(Wood 1971)* and reduced evaporation *(Myrup 1969)*. A reduction in urban moisture, with a corresponding reduction in latent heat energy, may also account for anomalous precipitation patterns *(Terjung et al. 1971; Boatman 1974)*. On the local scale uncertainty has been expressed whether the overall water contribution from the city is reduced compared to rural areas since much water vapor is released by combustion, industry, and cooling operations.

Project METROMEX (*METRO*politan *M*eteorological *EX*periment) was initiated in 1971 to statistically and physically evaluate the possible modification of weather and climate by an urban-industrial complex. Recent studies by the University of Wyoming in Project METROMEX focused on the problem of urban moisture *(Sisterson 1975)*. Data were acquired from the instrumented Wyoming research aircraft and instrumented meteorological weather mobiles, along with surface networks operated by cooperating groups (Illinois State Water Survey, St. Louis City and County Air Pollution Agencies).

Three aspects of urban moisture were investigated: (1) relative magnitudes of anthropogenic sources and sinks, (2) the three-dimensional structure of the moisture field, and (3) evaluation of the moisture budget components.

SOURCES AND SINKS OF MOISTURE

Estimates of automobile and industrial sources of water vapor were compared to potential evaporation calculations. The industries chosen in this study warranted investigation because of their size and location in the St. Louis area. The results of water vapor production rates (gm hr^{-1}) for anthropogenic sources and potential evaporation for the urban area are shown in table 1. Even if only a fraction of the radiation energy is used for evaporation, it is apparent that potential evaporation (for a 30-km by 30-km surface area) is several orders of magnitude greater than anthropogenic moisture sources. However, industrial sources are essentially point sources of water vapor. If the potential evaporation is considerd for an area only 3 km by 3 km, the rate of water vapor production approaches that of the major industrial sources. Thus, during the daylight hours, anthropogenic sources do not appear to be of consequence except on the local scale. At nighttime, when potential evaporation is greatly reduced and mixing is limited, anthropogenic sources are indeed a relevant factor in the urban water balance, so that the urban atmosphere at night may be more moist than the rural atmosphere.

Hygroscopic aerosols, photochemical reactions, and precipitation are major moisture sinks for an urban atmosphere. In this study, cases were chosen on non-precipitation days, so the precipitation component was neglected. Particulate mass concentrations of 100μgm m^{-3} (0.5μm size) have been reported for a highly polluted day in Los Angeles, California. In the extreme case, all particles are assumed to be hygroscopic salt particles at a relative humidity of 90 percent. For this case, the maximum change in specific humidity in the urban area (30 km by 30 km by 1.5 km) would be only 2.75 x 10^{-4} gm kgm^{-1}. This amount is insignificant and cannot be detected by moisture measurement.

Investigation of photochemical reactions in the urban atmosphere was limited to the formation of sulfuric acid, the most common and prolific photochemical pollutant. In the extreme case, all sulfur dioxide was assumed to react with water vapor to form sulfuric acid. In all cases, the water vapor necessary to convert all the SO_2 to H_2SO_4 was at least one order of magnitude less than the water vapor emissions from the industry.

Sulfuric acid is also deliquescent at high concentrations. The excess water vapor between industrial source and reaction requirements was used to dilute sulfuric acid concentrations in the industrial plumes. The Labadie power plant plume showed the greatest potential concentrations of sulfuric acid. Only if the environmental relative humidity is greater than 94 percent could sulfuric acid from the Labadie plant absorb ambient water vapor—again assuming

Table 1.—Urban area sources of water vapor

Classification	Source	Water vapor (gm hr^{-1})
Auto	Automobile	2.3×10^8
Refineries	Amoco	1.2×10^8
	Shell	3.0×10^8
Power Plants	Meramec	2.0×10^7
	Portage des Sioux	1.9×10^7
	Labadie	5.8×10^7
Cement	Alfa	2.9×10^7
	Missouri Portland	7.6×10^7
Steel	Granite City	1.8×10^8
Nature	Potential Evaporation	6.7×10^{11}

all SO_2 converted to H_2SO_4. The photochemical reaction of sulfuric dioxide and water vapor is therefore clearly not a significant factor in the extraction of water vapor from the urban atmosphere on the mesoscale, and in general, the deliquescense of sulfuric acid is insignificant.

ST. LOUIS CASE STUDY— 26 JULY 1974

Atmospheric moisture patterns are influenced by advection, turbulent mixing, and local sources and sinks of moisture. In the METROMEX field studies, aircraft transects were chosen so that unique air columns were successively intercepted at two flight levels as they passed over the urban area. The flight pattern thus minimized advection. Horizontal turbulent mixing was found to be insignificant and downward entrainment of dry air into the mixing layer was initially assumed insignificant with the presence of a subsidence inversion.

Because surface data were acquired from fixed stations, the time rate of change of surface moisture measurements included advection. Calculations showed that surface moisture advection on the mesoscale was insignificant. Local advection, however, was not assessable and may be important.

Temperature and moisture comparison between corrected weather mobiles, hygrothermographs, and telemetry stations at locations where data from all three uniquely different sources could be compared, showed consistent results. A similar consistence was observed between aircraft and radiosonde measurements in the free atmosphere. It is important to recognize that the characteristic of the moisture anomalies described in this section were consistent among four independent types of instruments.

Data from 26 July 1974 for 1530 to 1630 CDT are presented to illustrate moisture patterns that have been observed on a number of fair summer days. Low-level winds on this day were northerly with speeds less than 5 m sec^{-1}. Specific humidity and potential temperature patterns are shown for the surface at 1600 CDT (fig. 1). Dry regions exist along the northern, southern, and western edges of St. Louis, corresponding to major residential and light industrial land-use characterizations (fig. 2). Heat islands are apparent north of the city and along the southern edge. Because these analyses are based upon individual stations, local effects influence station readings, and small regions of low moisture and high temperatures are apparent *(Chandler 1967, Kopec 1973)*. Weather mobile data also show as much as 2 gm kgm^{-1} and a 1C variation in moisture and temperature, respectively, over distances of 1 km.

Patterns of specific humidity and potential temperature are shown for 450 m MSL (300 m AGL) in figure 3. A single widespread dry region exists along the southern edge of St. Louis, with tongues of dry air extending along the eastern and western edges of the metropolitan area. A single heat island is also apparent and corresponds to the dry region. Both humidity and temperature patterns are reasonably well correlated with those on the surface. The patterns of specific humidity and potential temperature patterns at 900 m MSL (fig. 4) correlate well with those at 450 m MSL. Both dry regions and heat fields are more widespread at the upper level.

From data acquired at the three levels between 1530 and 1630 CDT, three-dimensional analyses of the moisture fields in the mixing layer were constructed. Isopleth analysis of the specific humidity is shown for 10.2 gm kgm^{-1} (fig. 5) and 11.8 gm kgm^{-1} (fig. 6). A plume-like structure with an hourglass configuration is evident. The drier surface air is apparently mixed vertically through the mixing layer. Measurements of the wind field convergence also

Figure 1.—Specific humidity (gm kgm^{-1}) and potential temperature (°K) patterns for the surface at 1600 CDT. Heavy dashed lines show weather mobile transects. The shaded region defines urban and suburban areas.

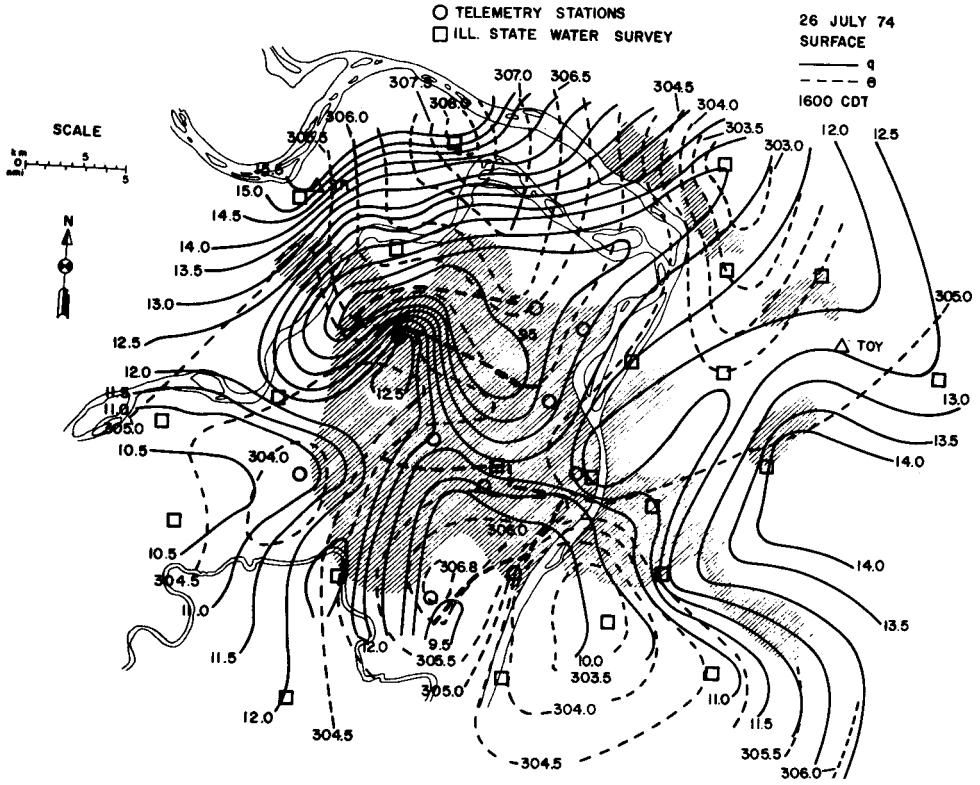


Figure 2.—St. Louis and surrounding area land use characteristics. Roadways and their corresponding route numbers are shown. The solid triangles represent the St. Louis and Troy navigational vortacs.

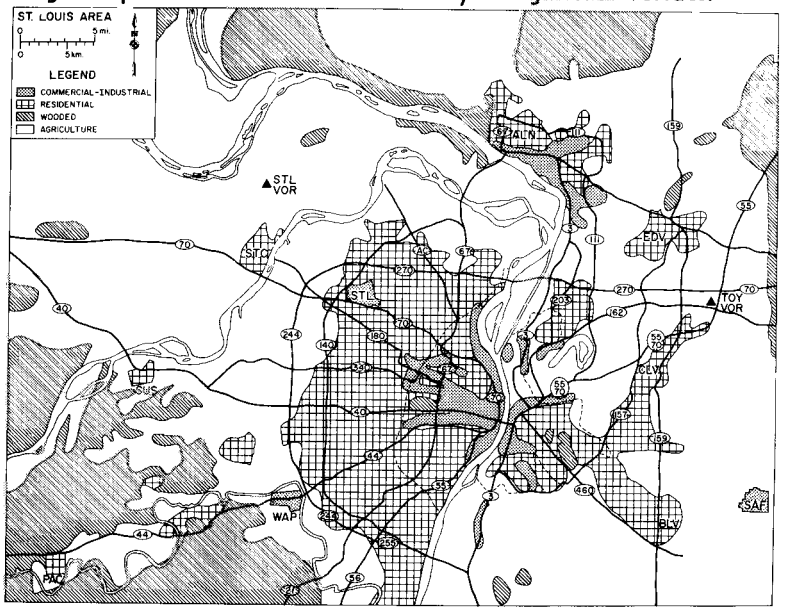


Figure 3.—Specific humidity (gm kgm^{-1}) and potential temperature (°K) patterns at 0.45 km MSL (1530-1630 CDT).

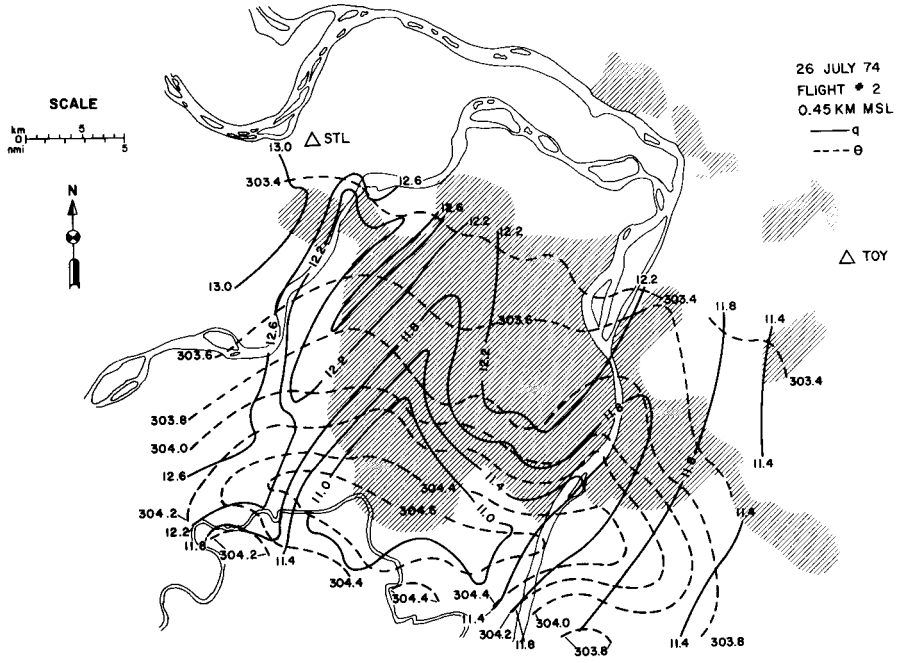


Figure 4.—Specific humidity (gm kgm^{-1}) and potential temperature (°K) patterns at 0.9 km MSL (1530-1630 CDT).

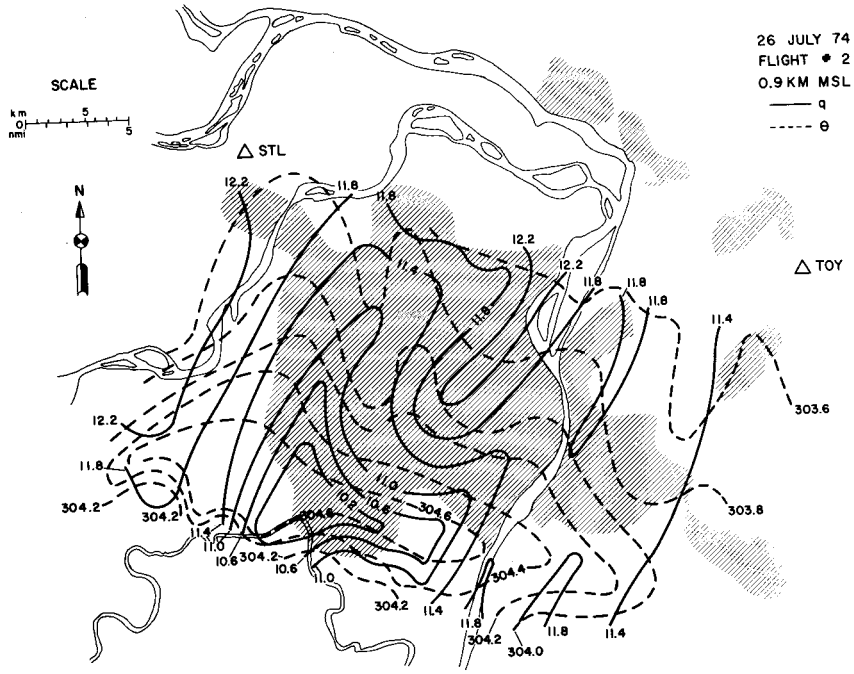


Figure 5.—Three dimensional analysis of the 10.2 gm kgm^{-1} isohume (1530-1630 CDT) for 26 July 1974.

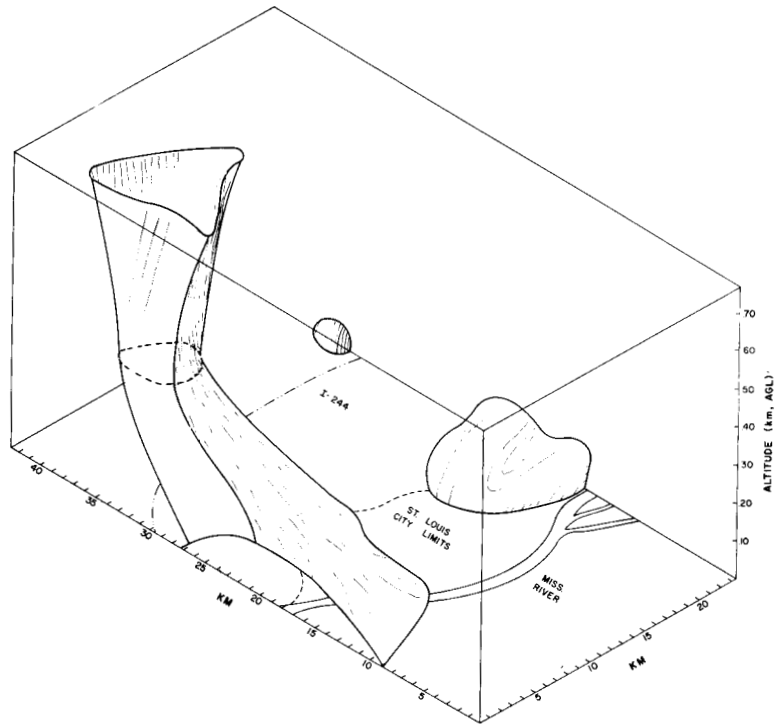


Figure 6.—Three dimensional analysis of the 11.8 gm kgm^{-1} isohume (1530-1630 CDT) for 26 July 1974.

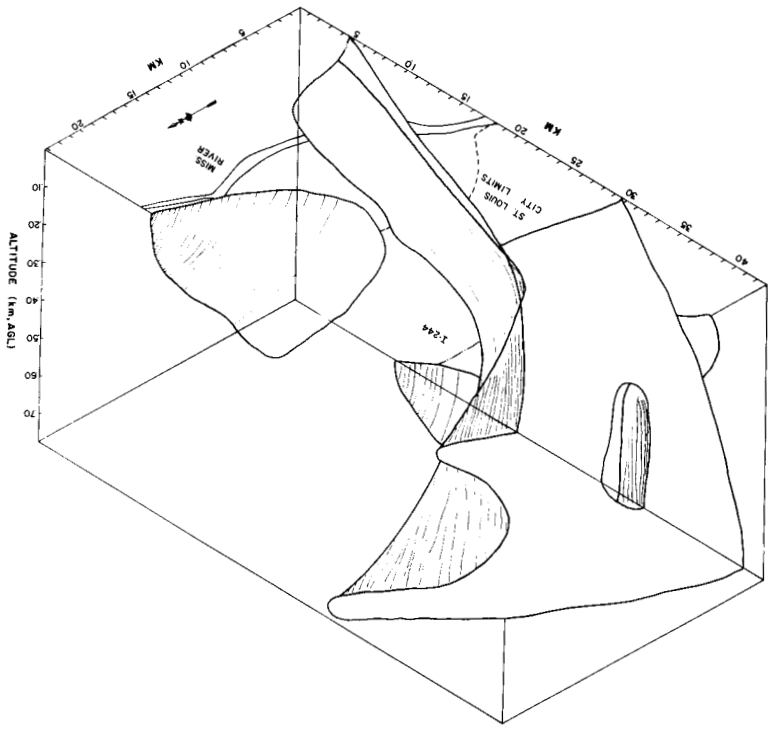


Figure 7.—Upwind aircraft sounding at 1533 CDT.

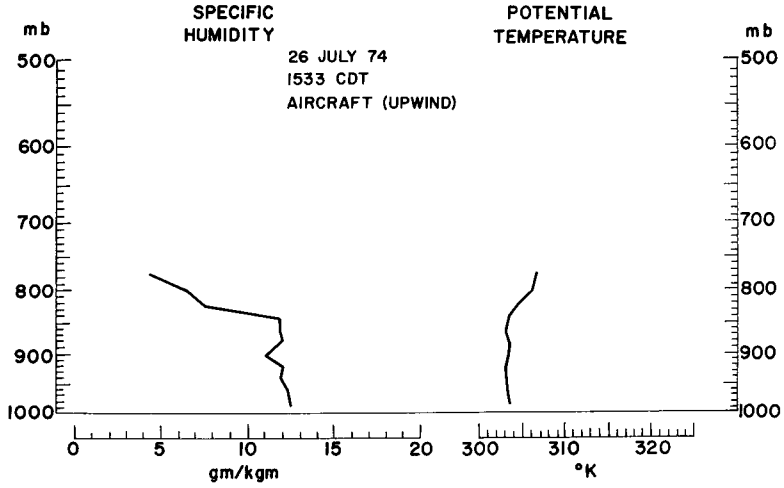


Figure 8.—Tower Grove Park radiosonde sounding at 1500 CDT.

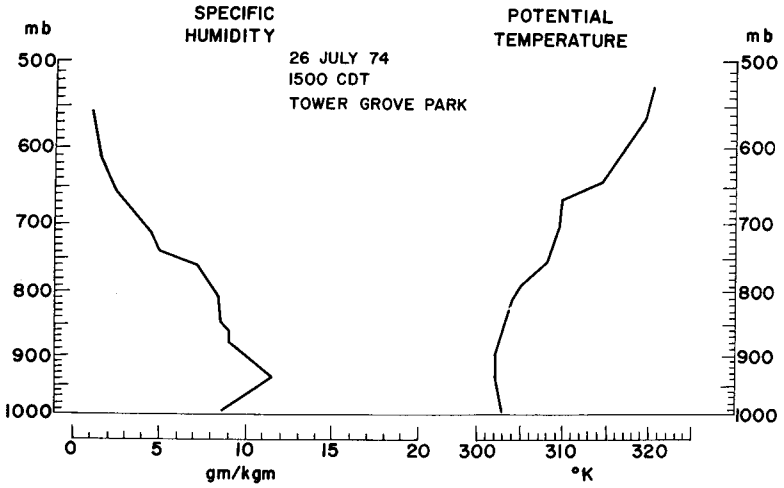
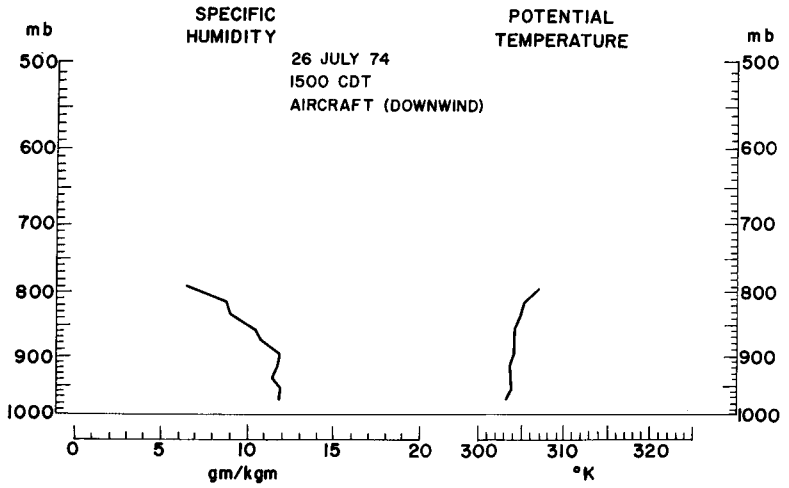


Figure 9.—Downwind aircraft sounding at 1500 CDT.



support the concept of convergence and ascent in the dry regions.

Aircraft and radiosonde soundings were also analyzed for the effects of urban modification on vertical moisture profiles. Aircraft soundings were extrapolated to the surface, using local surface values of humidity and temperature. Likewise, values from an aspirated psychrometer established the surface temperature and humidity for radiosondes. Three soundings (upwind, over, and downwind to St. Louis), taken within a period of 30 minutes, are shown in figures 7 to 9. Particular attention is focused on the lowest 50 mb moisture profile of each sounding. The upwind sounding shows a slight decrease in specific humidity with height. The sounding at Tower Grove Park, (5 km southwest of downtown St. Louis), taken near a large concrete area, shows a large increase of specific humidity with height. The downwind sounding shows only a slight increase of humidity with height. These soundings show that within the lowest 50 mb the urban surface is drier than the air above 950 mb on this day. These features are characteristic of a number of case study days. Hence, as air columns pass over the urban area from a region of high surface humidity (upwind) to a region of lower surface humidity, the mixing of dry air into the columns reverses the low-level humidity gradient and decreases the average specific humidity of the columns.

These soundings also show that the inversion is elevated over the urban area by 600 m. The sharp moisture discontinuity at the base of the inversion of the upwind sounding is not present over the city. There is an apparent eroding of the air beneath the inversion, probably attributable to nonuniform downward entrainment of dry air. This violates the previous assumption of negligible entrainment into the mixing layer. This entrainment term could not be assessed, but it is apparent that downward mixing across the inversion will also dry out the columns.

Overall, the urban-influenced atmosphere is drier than the surrounding rural area. Because there is less moisture potential at the city surface (vegetation, porous soils, etc.), less energy is used for evapotranspiration purposes. The excess energy is then utilized between sensible heat energy and ground stored energy, which generally causes the urban atmosphere to be hotter.

In summary of the 26 July 1974 study, dry regions are found within the St. Louis urban area. These regions of low specific humidity correlate well with impervious surfaces found in the densely populated residential areas and light industrial areas. Although the moisture content of air columns passing over the city may decrease from downward entrainment of dry air from above the mixing layer, reduced evapotranspiration at the surface clearly contributes to a reduction in average specific humidity of the columns. It can be inferred that up to 50 percent of the St. Louis area *(Marotz and Coiner 1973)* is represented by modified surfaces. Thus the urban surface environment is drier due to reduced evapotranspiration from widespread impervious surfaces.

RELEVANCE TO URBAN-DWELLERS

From energy budget considerations, nearly equal amounts of radiation are available at both urban and rural surfaces *(Maisel 1971, Rouse et al. 1973)*; however, less radiation is used as latent heat energy, so that sensible heat energy and ground stored energy must be greater in the urban area. Loose soil and plant material characteristically are very poor heat conductors and have a low heat capacity. Hence all heat transactions take place in a thin surface layer in most rural areas. In contrast, urban areas have massive surfaces of stone, brick, concrete and asphalt. These have better heat conductivity than soils and therefore may be warmed to ap-

preciable depth by incoming solar radiation. Nocturnally the stored heat is gradually released, which keeps the city surfaces warmer than surrounding grassland or trees. In addition, the heated vertical surfaces of buildings radiate toward each other and do not lose heat by radiation toward the sky as a horizontal surface in the open country would *(Landsberg and Maisel 1972)*.

The increase in sensible heat energy (the heat island) is a well-documented phenomenon in urban areas. High environmental temperatures affect health. Prolonged exposure to high temperatures associated with summer heat waves can result in death either as a primary cause or as a contributing factor in heart disease, strokes, and pulmonary disorders. There is evidence to suggest that a large percentage of heat-related deaths may be of man's own design by climate modification through urbanization. Clarke and Bach *(1971)* showed a relationship between average daily temperature and deaths attributed primarily to heat during the July 1966 St. Louis heat wave, in which 500 deaths occurred in East St. Louis, Illinois. Although no heat deaths occurred at an average temperature of 31.7C, deaths increased markedly with every one-degree increase in temperature above 32.2C (assumed the critical level). A rise of the average daily temperature of only 0.6C above 32.2C resulted in 11 heat deaths. Seventy-three heat deaths occurred when the average daily temperature was 35C. This 2.8C increment of average daily temperature is about the same as the average temperature difference between the urban and suburban environments, based on the afternoon and evening temperatures obtained in Clarke and Bach's study.

Other effects of the urban moisture climate may also contribute to man's discomfort in his atmospheric environment. The reduced moisture content of urban-influenced air may locally deprive storms of latent heat energy, so that the intensity of thunderstorms could be expected to decrease over the urban area, as observed by Boatman *(1974)*. This may further result in precipitation anomalies observed downwind of large urban areas. The small amounts of water vapor absorbed by hygroscopic aerosols generated from industrial effluents create haze particles that severely reduce visibility in the urban area. The effect of increased moisture from industry at night when mixing is only within a shallow layer would be expected to increase urban humidity, such that the city may be more moist than surrounding country air. This may also explain the greater tendency for fog in urban areas.

Finally, now that evidence for an urban area as a potential weather modifier on the basis of its physical presence is realized, some recommendations may be offered that would help to make the city a more comfortable place in which to work and live. From energy and moisture budget considerations, green belts or vegetated areas are necessary within our cities. Green belts would not only help to embellish the downtown image, but also moderate the cities temperature. Large asphalt parking lots should be transected with trees and shrubs to reduce overheating. Fountains and small parks should be constructed within the heart of the city where the greatest percentage of concrete and impervious surfaces exist. Gardens and vegetation could be planted on rooftops. All of these modifications of the urban moisture budget would contribute to a moderation of the daytime temperature excess of the urban heat island.

CONCLUSIONS

The lack of available moisture from the urban surface leads to increased sensible heat energy and ground stored energy. Properly spaced green areas are perhaps the most important means of controlling the urban temperature excess. The urban heat island effect

could also be reduced in torrid latitudes by using building materials that have lower heat conductivity and capacity. Building with different materials and colors, through changes in albedo and heat absorption, would cause differentials in heating and encourage mixing and ventilation. On the other hand, cities in high latitudes may be purposefully constructed to strengthen the heat-island effect. If the effects of urban development on the local climate are considered in the urban planning process, climate modification can be purposely controlled toward man's comfort rather than allowed to inadvertently develop to man's distress.

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Anthropogenic Moisture Production and Its Effect on Boundary-layer Circulations over New York City

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Part of this work was performed under the auspices of the U. S. Energy Research and Development Administration, and part was supported by the Climatic Impact Assessment Program of the U. S. Department of Transportation.

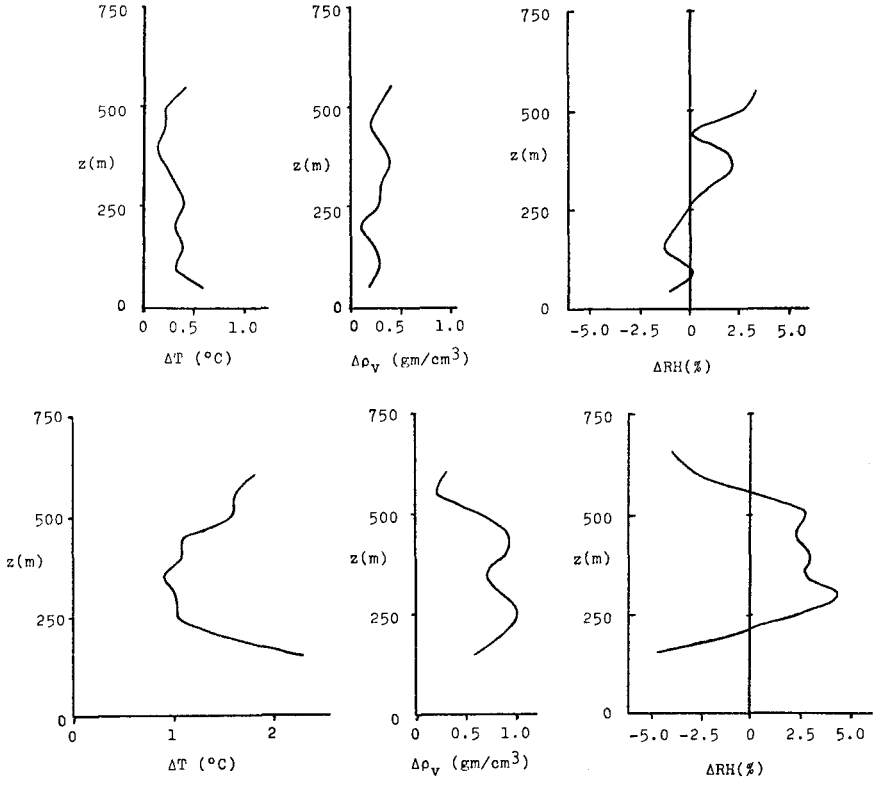
ABSTRACT.—A heat and moisture excess over New York City is shown to exist by the analysis of helicopter soundings of temperature and wet-bulb depression. The magnitude of the temporal and spatial distribution of anthropogenic moisture emissions in New York City were estimated from fuel-usage data. The URBMET urban boundary-layer model was used to evaluate the effects on the dynamics of the urban boundary layer resulting from the observed urban moisture excess. Work is currently in progress to determine the fraction of the observed moisture excess over New York that is due to anthropogenic sources.

UNTIL RECENTLY, studies of the atmospheric moisture content at the surface in and around cities have shown that, on the average, cities are somewhat drier than their rural surroundings. Average relative humidities have generally been found to be several percent lower in cities than in nearby rural areas; also, absolute humidities were found to be slightly lower in the built-up areas. The main reason given for these humidity differences was the lower evaporation rates in the city than in the country. This reduction occurs because rainfall is retained by vegetation-covered rural surfaces, while rapid runoff occurs in asphalt- and concrete-covered cities *(Peterson 1969)*.

Recently, Chandler *(1967)* obtained atmospheric-moisture data from a series of automobile transverses in and around London during three summer nights of low wind, clear skies, and well developed urban heat islands. He found that measured urban vapor pressures were higher than nearby rural vapor pressures, and found the reverse true for relative humidities. He attributed the higher nighttime urban absolute humidity to the lower amount of dew formation in urban areas and to the addition of water to the urban atmosphere from anthropogenic sources.

Similar results were found by Ackerman *(1971)* in an analysis of seven years of dew-point data from urban Midway Airport in Chicago and from rural Argonne National Laboratory, 125 miles southwest of Chicago. Results showed: (1) an urban moisture excess when all of the data were considered, (2) an urban moisture excess for the nighttime data, (3) an urban moisture deficit for the daytime data, and (4) an urban moisture excess for the winter daytime data. Thus during the times when combustion was a major source of moisture, the urban atmosphere was more moist than the rural atmosphere. These results are consistent with those of Auer and Dirks *(1974)*, who found that the air over St. Louis was drier than that over its nearby rural areas during summer daytime periods. Urban moisture excesses have also been found by Kopec *(1973)* and Goldreich *(1974)*, while Hage *(1972)* showed that anthropogenic moisture emissions can enhance the forma-

Figure 1.—Average vertical distribution of urban minus rural values of temperature ΔT, absolute humidity $\Delta \rho_v$, and relative humidity ΔRH for daytime periods (upper curves) and nighttime periods (lower curves).



tion of low-temperature fog in the city of Edmonton.

Vertical and horizontal moisture distributions in and around New York City were studied by Lorenzen *(1972)* and Bornstein *et al. (1972)* to determine the vertical extent of urban-rural moisture differences. Sixty-two helicopter soundings of temperature, wet-bulb depression, and pressure height were obtained during three early-morning periods and during one late-afternoon period in 1964.

Results from the analysis of the above data (fig. 1) showed that the following values are larger at night than during the day: (1) urban heat-island values, (2) urban excesses in absolute humidity, (3) urban relative humidity deficits below 250 m, and (4) urban relative humidity excesses at heights between 250 and 500 m.

The data used by Bornstein *et al. (1972)* were collected from 1964 to 1969 as part of a U.S. Public Health Service sponsored grant to the late Ben Davidson of the Department of Meteorology and Oceanography at New York University. As described by Davidson *(1967)*, the main goal of the project was to develop a sophisticated model for the prediction of the distribution of SO_2 in the New York City metropolitan area *(Shieh et al. 1969)*.

Though the data obtained by the NYU project were used in various studies of the urban boundary layer over New York City, the original data set was never published, due to the untimely death of the project's principal investigator. In the belief that NYU/NYC data set is unique, and that it could be extremely useful to persons interested

in the urban boundary layer over New York City, much of the original data has recently been published by Bornstein *et al. (1975b)* under a grant from the U. S. Environmental Protection Agency and is on file with its Meteorology Laboratory at Research Triangle Park. An important component of the NYU/NYC data is an area and point-source emission inventory for the production of SO_2, heat, and moisture from anthropogenic sources within the New York City metropolitan area during 1965.

The main goals of the current research reported here are: (1) to determine the magnitude and variation in time and space of the anthropogenic moisture flux in New York City, (2) to determine the effects of the observed moisture excess on the dynamics of the urban boundary layer over New York City, and (3) to determine the fraction of the observed moisture excess over New York City that is due to each of the following: area-source emissions, point-source emissions, and reduced nighttime condensation rates in the urban areas, as compared to those in nearby rural areas.

The first of these goals has been carried out under a grant from the U. S. Environmental Protection Agency to the Department of Meteorology at San Jose State University, while the second part has been accomplished by use of the computer facilities at Lawrence Livermore Laboratory. The third section is currently being carried out under a grant from the National Science Foundation to the Department of Meteorology at San Jose.

In carrying out the second and third parts, the two-dimensional, nonsteady "URBMET" (for urban meteorology) urban boundary-layer model of Bornstein *(1975)* has been used to predict the temporal and spatial distribution of wind, temperature, and moisture within the urban boundary layer. The surface boundary condition for the absolute humidity in these simulations is being obtained from the temporal and spatial distribution of the anthropogenic moisture production in New York City, as obtained from the fuel-use inventory compiled during the original NYU air-pollution project.

ANTHROPOGENIC MOISTURE EMISSIONS

Most of the study region (fig. 2) has an elevation that is close to mean sea level, but the northwestern 10 percent of the area consists of highlands that range in elevation from 250 to 500 feet above mean sea level. About 30 percent of the study area is water, while 60 percent is open country, and 10 percent has been built up for urban and suburban uses.

During the original NYU project, an unpublished inventory of the annual emission of SO_2 from the known area and point sources in the New York Metropolitan region was compiled. Point-source emission information was obtained through the use of questionnaires, while area-source emissions from both fixed and mobile sources were computed from fuel-use data obtained from the following sources: (1) the U. S. Bureau of Mines, which publishes an annual report on the shipments of fuel oil; (2) the New York Oil Heating Association; (3) the American Petroleum Institute; (4) the New York City Council Committee on Air Pollution; (5) the New York City Housing Authority; (6) the New York City Air Pollution Control Agency; (7) the NYC Fire Department; and (8) the New York City Licensing Agency, which controls the installation, registration, licensing, and insurance of each furnace or power plant in New York City. The seven main types of fuel consumed in the New York City area, the uses to which they are put, and their annual rates of consumption are listed in table 1.

Because fossil fuels are composed of carbon, hydrogen, sulfur, etc., the com-

Figure 2.—Topography of study area with values in feet above sea level. Also shown by the cross-hatched area are the built-up areas of New York City.

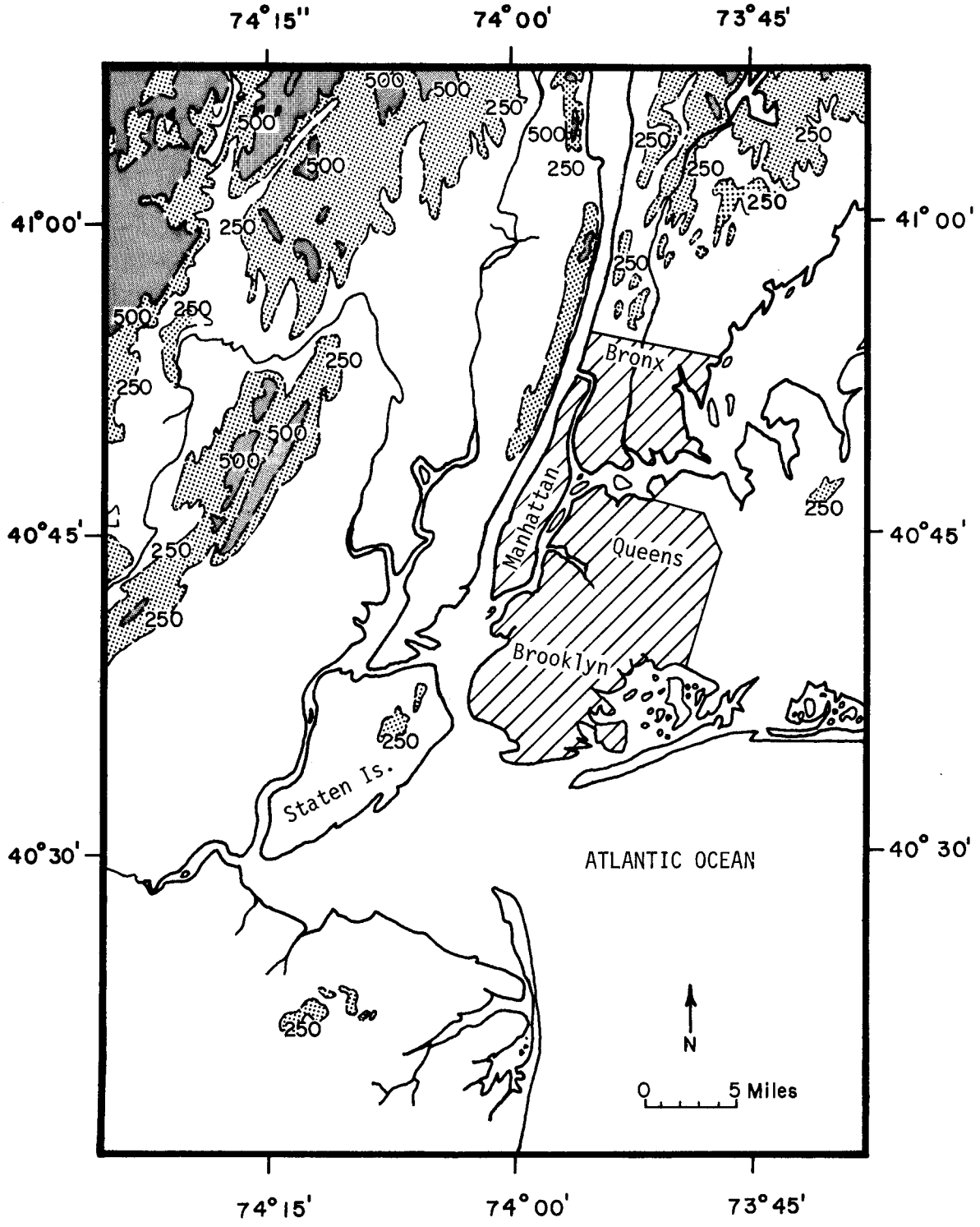


Table 1.—Fuel Consumption in New York City in 1965

Fuel type	Uses	Annual consumption
Bituminous coal	Space-heating and firing of industrial boilers	5.4×10^6 tons
Anthracite coal	Residential space-heating	0.72×10^6 tons
Distillate oil #4	Space-heating of small apartment houses	1.5×10^9 gal.
Residual oil #6	Space-heating of large apartment houses and operation of industrial plants and factories	2.6×10^9 gal.
Natural gas	Fuel in power plants, energy for industrial plants, space-heating, and home cooking	1.67×10^{11} ft.^{3}
Gasoline	Automobiles, trucks, and buses	1.1×10^9 gal.
Diesel	Automobiles, trucks, and buses	66.6×10^6 gal.

Table 2.—Composition of natural gas

Paraffin hydrocarbon	Fraction of total mass	Water content
	percent	*percent*
CH_4	93.45	186.90
C_2H_6	3.67	11.01
C_3H_8	1.78	7.12
C_4H_{10}	0.65	3.25
Others	0.45	—
Total	100.00	208.28

bustion of these fuels produces oxides of sulfur, oxides of nitrogen, carbon monoxide, carbon dioxide, aldehydes, hydrocarbons, particulates, and water vapor. The quantities of these products put into the atmosphere depend on the rate of the combustion process, the content of impurities per unit mass, the equipment used for the combustion process, and the kinds of control devices that might have been installed. For example, in the steam boilers of Consolidated Edison power plants, 1.4 lbs. of steam are added per 100 lbs. of residual oil consumed. This is done in order to atomize the oil, so as to increase the efficiency of the combustion process. Thus the water-vapor emission rate from these stacks is greater than from other point sources.

The basic equation for the production of water from the combustion of coal (after the hydrocarbons have been broken down) is

$$2H_2 + O_2 \rightarrow 2H_2O \quad , \qquad [1]$$

while the general formula for the combustion of oil and gas is

$$C_xH_y + (x+\frac{y}{4})\ O_2 \rightarrow x\ CO_2 + \frac{y}{2} H_2O \quad , \qquad [2]$$

where

$$y = 2x + 2 \qquad [3]$$

if the hydrocarbon C_xH_y is saturated. Thus for coal, one gram of hydrogen produces 18 grams of water, while y grams of H_2 per mole of gas or oil produces 18Y/2 or 9Y grams of water per mole, where 18 is the ratio of the molecular weights of water and hydrogen.

The water production from each component of natural gas (table 2) was evaluated by multiplying the coefficient of the final term of equation 2; i.e., Y/2, by the percentages in the middle column of the table. Water-production factors for each of the seven fuel types used in New York City are shown in table 3, where the liquid water content of coal is determined by drying under standard conditions for 1 hour at 104 to 110 C.

The five boroughs of New York City (identified by name in figure 1) were gridded into 1 by 1 mile areas, and the following equation was used to evaluate

Table 3.—Composition by percent of total mass of the fuels used in New York City

Fuel type	H_2O (%)	Gaseous H_2O (%)	Liquid H_2O (%)	Total H_2O (%)	H_2O released per unit
Bituminous coal	5.14	46.26	2.0	48.26	0.4826 lb/lb
Anthracite coal	2.70	24.30	2.2	26.50	.265 lb/lb
Distillate oil	11.63	104.67	—	104.67	7.955 lb/gal
Residual oil	11.63	104.67	—	104.67	8.478 lb/gal
Natural gas	—	208.28	—	208.28	.11 lb/ft^3
Gasoline	15.00	135.00	—	135.00	9.315 lb/gal
Diesel	15.00	135.00	—	135.00	9.315 lb/gal

Table 4.—Percentage of SO_2 emitted from each fuel type in each Borough of New York City

Fuel type	Bronx	Brooklyn	Queens	Manhattan	Staten Island
Bituminous coal	1.45	8.61	32.53	37.26	70.80
Anthracite coal	2.16	1.34	.39	1.31	1.29
Distillate oil #4	8.60	13.91	10.26	1.13	5.99
Residual oil #6	87.18	75.69	56.05	59.88	21.53
Natural gas	.01	.01	.01	.01	.01
Gasoline	.39	.29	.48	.28	.22
Diesel	.21	.15	.28	.13	.16
Total	100.00	100.00	100.00	100.00	100.00

the magnitude of the annual anthropogenic moisture production M_A from each of the grid areas:

$$M'_A = \sum_{i=1}^{7} \frac{S_A \cdot P_i \cdot M_i}{S_i} \quad , \qquad [4]$$

Definition and units for symbols are found at one end of this paper.

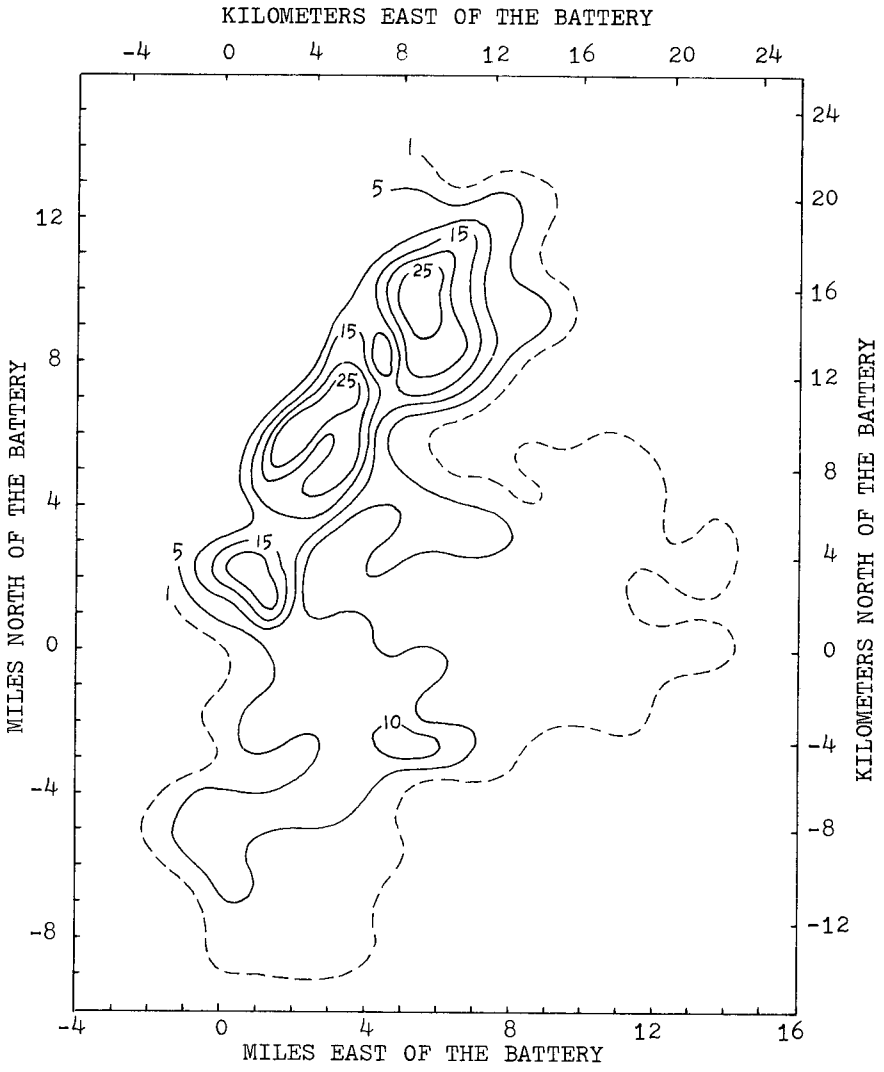
Note that the product of S_A (from the unpublished SO_2 inventory — now published by Bornstein *et al. (1975b)* — and P_i (table 4) gives the annual emission of SO_2 from the i-th fuel in a particular grid in tons per year. Values of P_i were kept constant in each borough because the use of each fuel in all of the grid areas was not available. Where the values were available, a random check showed that the magnitudes of P_i in a given borough were within ± 5 percent of the mean values used in Equation 4. The product of S_A times P_i divided by S_i (table 5) gives the annual use of the i-th fuel in the particular grids, while values of M_i (table 3) include the release of gaseous and liquid moisture.

Table 5.—Fuel type, sulfur content by weight, and sulfur emission factors for the seven fuel types used in New York City

Fuel type	Sulfur content (%)	SO_2 emission factor
Bituminous coal	1.875	75.0 lb/ton
Anthracite coal	.625	25.0 lb/ton
Distillate oil	.575	85.0 $lb/10^3$ gal
Residual oil	2.450	390.0 $lb/10^3$ gal
Natural gas	4 ppm	.6 $lb/10^6$ ft^3
Gasoline	.030	5.0 $lb/10^3$ gal
Diesel	.300	45.0 $lb/10^3$ gal

Annual area-source (fixed and mobile) emissions of anthropogenic moisture in New York City in 1965 in 10^{10} gm per year (fig. 3) were obtained by the summation of the seven partial emission rates of Equation 4. The origin of the grid used in the figure is at Battery Park, which is at the southern tip of Manhattan. The annual emission data were converted into average hourly fluxes (fig. 4), which have the units of 10^{-5} gm cm^{-2} hr^{-1} and can be used as

Figure 3.—Isopleth analysis of anthropogenic moisture production from area sources in New York City, in 10^{10} grams per year.

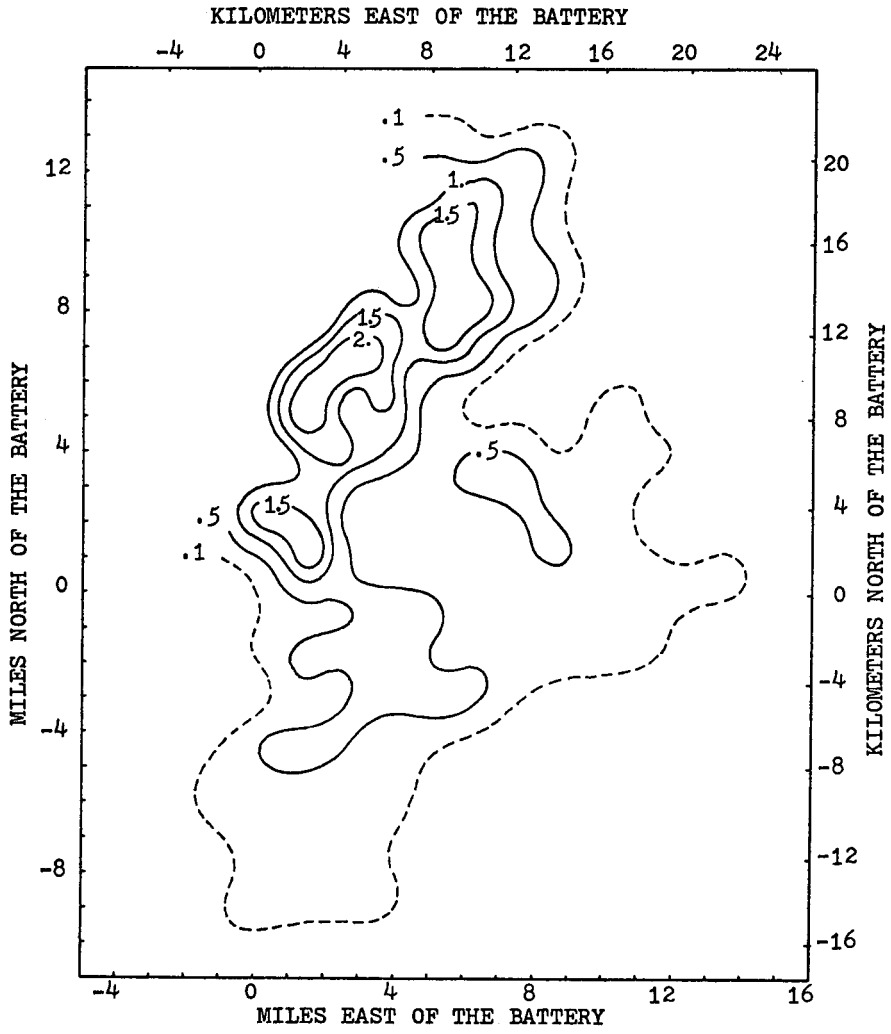


the lower (flux) boundary conditions in a numerical boundary-layer model of the urban atmosphere, as is being done by Tam *(1975)*.

Because some areas in New York City are source-free (such as Central Park and rivers around Manhattan), the fluxes of the previous figure were recomputed in terms of emission intensities; i.e., the emission of H_2O per unit of production area per time. This increased the maximum emission from 2.2 x 10^{-5} gm cm^{-2} min^{-1} to 4.3 x 10^{-5} gm cm^{-2} min^{-1}. The second value corresponds to a 22.6-cm-per-year annual evaporation rate, which is about 25 percent of the annual evaporation rate in the coastal Atlantic off of New York City *(Jacobs 1951)*.

For studies requiring a more detailed emission pattern, the above computations were repeated on 0.5 by 0.5-mile area-source grid over Manhattan *(Bornstein et al. 1975b)*, the region of maximum H_2O emission. In computing the emission rates for the finer grid, the

Figure 4.—Isopleth analysis of anthropogenic moisture production from area sources in New York City, in 10^{-5} gm cm^{-2} min^{-1}.



emissions from the larger areas were assumed to be homogeneously distributed over the built-up areas of the city, while emissions from the rivers around Manhattan and from Central Park were taken to be zero.

Anthropogenic moisture production in New York City by borough (table 6) shows that Staten Island contributes only a small fraction of the total area-source emission in New York City (and hence it is not cross-hatched in fig. 1), while Queens contributes the maximum amount of any borough. Production by fuel type (table 7) shows that residual oil produces more moisture in New York City than does any other fuel type, while production by source type (table 8) shows that domestic space-heating produces a larger amount of anthropogenic moisture than any other source type.

Estimates of the hourly emission rates of anthropogenic moisture from the fixed, but not mobile, area sources in New York City were made by using data obtained from timers attached to boilers located in selected buildings. The resulting data were used by Halpern

Table 6.—Anthropogenic moisture production in New York City by borough

Borough	Production (10^{12} gm/year)	Percentage of total
Queens	10.13	33
Brooklyn	8.60	28
Manhattan	7.06	23
Bronx	3.99	13
Staten Island	0.92	3
Total	30.69	100

Table 7.—Anthropogenic moisture production in New York City by fuel type

Fuel type	Production (10^{12} gm/year)	Percentage of total
Bituminous coal	2.35	7.7
Anthracite coal	.17	.6
Distillate oil	5.05	16.4
Residual oil	9.93	32.3
Natural gas	8.32	27.1
Gasoline	4.59	15.0
Diesel	.28	.9
Total	30.69	100.0

Table 8.—Anthropogenic moisture production in New York City by source type

Source type	Production (10^{12} gm/year)	Percentage of total
Domestic	10.91	35.5
Industrial	1.78	5.8
Government & commercial	4.18	13.6
Power plants	8.95	29.2
Motor vehicle	4.87	15.9
Total	30.69	100.0

et al. (1971) to relate the number of minutes per day that the boilers were in operation to the degree-day value D computed as follows:

$$D = 65 - \overline{T}, \quad \overline{T} \leqslant 65,$$

or [5]

$$D = 0, \quad \overline{T} > 65,$$

where $\overline{T}$ is the average daily temperature of a given day in °F.

The boiler-timer data were then used by Halpern et al. *(1971)* to develop the following equation, which relates the daily emission rate of H_2O from a particular area source to the annual emission rate from that area source:

$$M_D = \frac{0.7}{4871} D + \frac{0.3}{365} M_A. \quad [6]$$

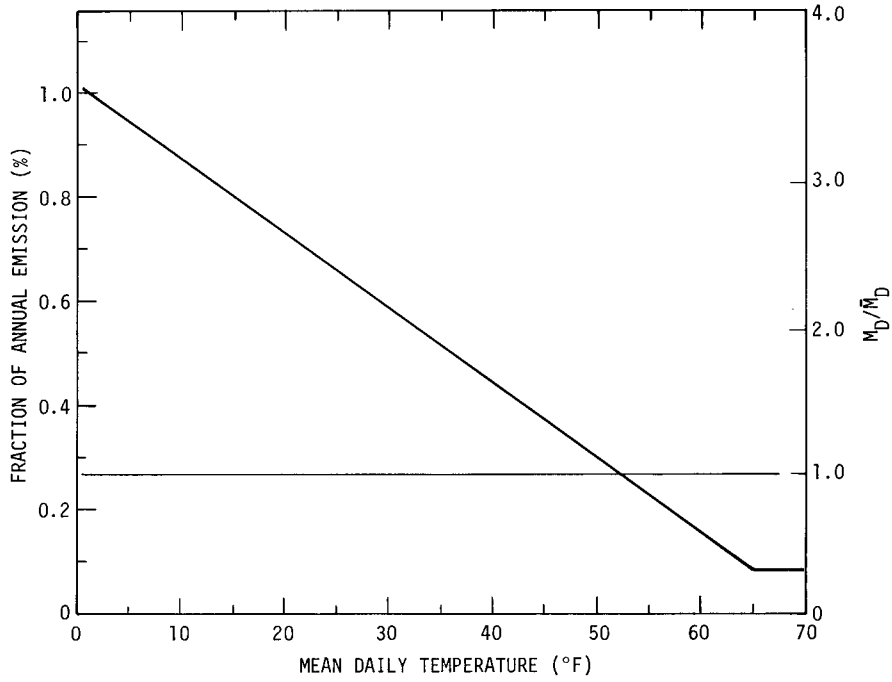
The above relationship shows that 30 percent of the annual emission of H_2O from each area source is due to the production of hot water at a uniform rate throughout the year. The remaining 70 percent is due to space-heating, which is dependent on the average daily temperature. Note that the annual sum of the daily degree-day values for New York City is the 4871 appearing in the equation.

If M_A were spread uniformly over the year, then on each day 0.27 percent of the total would be emitted. However, when Equation 6 is used to prorate M_A according to $\overline{T}$ (fig. 5), it is found that the value of $(M_D/M_A) \cdot 100$ percent varies linearly from 1.02 percent for a $\overline{T}$ of 0°F to 0.08 percent for a $\overline{T}$ equal to or greater than 65°F. Thus the emission on a cold day can be as much as an order of magnitude greater than that on a hot day.

The same boiler-timer data were used by Halpern *et al. (1971)* to develop curves showing the diurnal variation in winter, when most of the fuel is consumed for space-heating, and in summer, when most of the fuel is used for the production of hot water in the hours near sunrise and sunset. These results were used by Leahey and Friend *(1971)* to compute the spatial distribution of the annual and daily production of anthropogenic heat in New York from area sources due to fossil fuel use. They can be used to produce the same information for the anthropogenic moisture flux in New York City.

In the New York City area in 1965 there were 378 point sources of SO_2 that were found to have an annual emission rate of at least 100 tons of SO_2. The 205 point sources within the city emitted

Figure 5.—Fraction of annual area-source emission of moisture in New York City as a function of mean daily temperature. Also shown is the ratio of the daily emission M_D to the uniform daily emission $\bar{M}_D$ (shown as the horizontal line).



3.67 x 10^5 tons of SO_2 per year, or about one-half of that emitted by the area sources within the city.

In general, the rate of consumption by power plants, industrial processes, and automobiles changes only slightly throughout the year. However, the emission rates of some industrial and commercial sources do vary significantly over the year, and the emission rates of many point sources do have a diurnal variation. Where it was available, this information has been tabulated by Bornstein *et al. (1975b)*, as has been the stack height and heat-emission data needed in plume-rise calculations. Thus the NYU/NYC data set contains the information needed to evaluate the area-source and point-source emissions of anthropogenic moisture in New York City for use as the surface flux boundary condition for moisture in an urban boundary-layer model of New York City.

NUMERICAL SIMULATIONS

In the basic URBMET model, finite difference solutions to the vorticity and energy equations are obtained in a vertical plane in the direction of a constant geostrophic wind. The vertical fluxes of heat and momentum are assumed to be constant with height in a lower, analytical, surface-boundary layer, while they generally decrease with height in an upper, numerical finite-difference, transition layer.

The transition layer is assumed to be hydrostatic and Boussinesq, the latter assumption implying incompressible flow. All lateral gradients are assumed to be zero, except for that of the undisturbed pressure, which corresponds to a constant geostrophic wind. Adiabatic motions are also assumed, while diffusion effects in the direction of the geostrophic wind are assumed to be insignificant as compared to advective effects. Initially,

adiabatic lapse rates are assumed, as the heat-island simulations are assumed to commence at 1800 LST. The eddy-exchange coefficients used in the transition layer in URBMET are computed from a third-order-polynomial. Details on the formulation of the model can be found in Bornstein *(1975)*.

One modification of the original URBMET model in the current study was the inclusion of a continuity equation for water vapor, under unsaturated conditions, given by

$$\frac{\partial q'}{\partial t}=\frac{\partial (uq')}{\partial x}+\frac{\partial (wq')}{\partial z}+\frac{\partial}{\partial z}\left(K_q\frac{\partial q'}{\partial z}\right) \quad , \qquad [7]$$

where K_q was taken equal to K_H. Because of this equality, the surface layer profiles for q′ are identical to those for θ′, if q and q* replace θ and θ*, respectively, in the various surface boundary layer equations in B. In addition, the potential temperature θ is replaced by the virtual potential temperature θ_v. The two are related by

$$\theta_v=[1+0.61\ q]\theta \quad , \qquad [8]$$

where each of the three variables, in the absence of any initial variations, can be given by the sum of a space average constant and a perturbation quality resulting from the urban induced circulations. If

$$\theta' << \theta_m \quad , \qquad [9]$$

it can be shown that

$$\theta_v' \approx \theta' + 0.61\ \theta_m q' \quad , \qquad [10]$$

and thus θ'_v replaces θ′ everywhere in the model equations given in B. The second change in URBMET was concerned with the choice of the magnitude of the time step used in integration, and this is discussed in Bornstein and Robock *(1975a)*.

An interlaced grid was used in this study, as it considers velocity components to be the average inflow and outflow rates on horizontal and vertical elements of a cube. Previous studies have discussed the superiority of variable grid spacing in achieving high resolution near the surface and near discontinuities in surface characteristics. Accordingly, the 16 by 16 grid network used in the present study (table 9) possesses such a spacing near the surface, and in the vicinity of the city. A list of the boundary conditions on q′ currently used is given below.

Table 9.—Grid locations for θ, u and v grid points, with height above the surface z indexed by j, and distance from the center of the urban area x indexed by i

j/i	z (m)	x (km)
1	0	—30
2	12.5	—20
3	37.5	—12.5
4	62.5	— 7.5
5	87.5	— 5.0
6	125	— 2.5
7	175	0
8	225	2.5
9	275	5.0
10	325	7.5
11	375	10.0
12	450	15.0
13	600	22.5
14	850	32.5
15	1200	47.5
16	1650	67.5

$$q'=a(x,t) \quad , \quad z=0 \quad , \qquad [11]$$

$$\text{continuity of } q' \text{ and } \frac{\partial q'}{\partial z} \quad , \quad z=h \quad , \qquad [12]$$

$$q'=0 \quad , \quad z=H \quad , \qquad [13]$$

$$\frac{\partial (uq')}{\partial x}=0 \quad , \quad \text{upwind boundary} \quad . \qquad [14]$$

At each time step, following an initialization process described below, the following is performed: determination of the new values of θ'_v and q′ at the surface; construction of the constant flux layer using the latest values of θ'_v, q′, and U at the surface, and at the lowest finite difference grid; and determination of the new q′ θ'_v, ζ, Ψ, u, w, v, and U fields, respectively, using the newest available values of all parameters and done in a

manner described in Bornstein and Robock *(1975a)*.

The initial conditions were considered to be those at the beginning of an urban heat-island episode (at 1800 LST), and thus the following initialization procedure was carried out. First, the URBMET model was used to simulate the one-dimensional, neutral, dry planetary boundary layer over homogeneous terrain by assuming the following conditions

$$\frac{\partial}{\partial x} = w = 0 \qquad [15]$$

$$Y = \Gamma \qquad [16]$$

$$\theta_v' = 0 \qquad [17]$$

$$q' = q_m = 0 \qquad [18]$$

Justification of the assumption contained in Equation 16 for the hours near 1800 LST can be found in the observations obtained over cities *(Bornstein 1968)*, as well as in those from rural O'Neill, Nebraska *(Kuo 1968)*.

Simulations were carried for values of the surface roughness parameter z_0 of 1 and 3m, and for values of the geostrophic wind u_g of 3 mps. The values for z_0 were chosen to be typical of areas with buildings of one and six stories *(Lettau 1969)*. The simulations were carried out using a constant value of 15 sec for the time step of integration, and were concluded when equilibrium conditions were obtained; i.e., when the final accelerations of the damping inertial oscillation were less than 0.1 cm sec^{-1} hr^{-1}.

The resulting equilibrium wind profiles were then used as the initial conditions for simulations reproducing the two-dimensional equilibrium distributions of wind over a rough city under conditions of neutral stability. Thus, the conditions expressed in equation 15 were no longer used, but as the results of these new simulations provided the initial conditions for the heat-island simulations discussed below, the conditions shown in equations 16 to 18 were still used.

Two-dimensional equilibrium wind distributions for the rough city cases were obtained after 3 hours of simulated time, using an equal advection and diffusion time step of 15 sec. The results of these simulations showed that the values of the total horizontal wind speed at the urban sites at heights up to several hundred metres were reduced in magnitude below those at corresponding heights at the upwind rural boundary. The maximum difference in speed occurred at the first grid point above the surface and over the downwind half of the city. The maximum upward and downward values of the corresponding vertical velocities were associated with the areas of maximum convergence and divergence at the upwind and downwind edges of the city, respectively.

Simulations were carried out to reproduce effects on the structure of the urban boundary layer, during the hours from 1800 to 1000 LST, resulting from higher urban than rural values of z_0 and surface temperature, but not q′. Hence, the conditions expressed by equations 16 and 17 were no longer used, but equation 18 was still applied.

The urban and rural surface cooling rates were estimated from the observations in and around urban Montreal by Oke and East *(1971)*. These observations indicated that the rural atmosphere near the surface cooled rapidly in the evening hours before midnight, while the urban atmosphere near the surface was maintained at a nearly constant temperature during the same period. After midnight both regions cooled at about 50 percent of the rate found at the rural site before midnight. Therefore, the magnitude of the heat island near the surface increased with time in the early evening and then remained constant until morning. Thus

the following surface cooling and warming rates were assumed:

Period (LST)	Urban (C hr^{-1})	Rural (C hr^{-1})
1800-2400	0.0	−1.0
2400-0600	−0.5	−0.5
0600-1000	1.0	3.0

These simulations were carried out by using a variable time step for both the advective and diffusive processes *(Bornstein and Robock 1975)*. The cooling rates prescribed above caused formation of a surface-based inversion in the rural areas, and the advection of cool rural air over the uncooled urban surface during the first 6 hours of the simulations caused formation of a slightly unstable layer near the urban surface. During the second 6 hours of simulation, the decreased surface-cooling rates slowed the rate of increasing stability at rural sites, while the urban cooling was unable to completely overcome the effects of advection, and thus Richardson numbers in the city remained slightly negative.

The horizontal wind field resulting after 6 hours of simulated time showed a region of decreased wind speeds, as compared to those at the upwind rural boundary. This region was found upwind of, and above, a region in which speeds are higher than those at the upwind boundary. A smaller region of decreased speeds was also seen downwind of the city near the surface. The corresponding vertical velocity field showed a region of sinking air over the city, sandwiched between two regions of upward motion.

The final simulations were carried out to reproduce the effects of an anthropogenic source of moisture on the structure of the urban boundary layer. Thus, the conditions expressed by equation 18 are no longer used; instead the background level of moisture q_m was arbitrarily set equal to 10 gm kg^{-1}. In addition, it was assumed that the surface value of q′ at the urban grid points increased by 0.25 gm kg^{-1} hr^{-1}.

Figure 6.—Distribution of the perturbation specific humidity q' in gm km^{-1} after 12 hours of simulated time; i.e., at 0600 LST, for the flow over a warm, rough, wet city; values represent the deviation from those at the upwind boundary. Parameters include a geostrophic wind of 3 mps, a rural z_0 of 1 metre, and an urban z_0 of 3 metres.

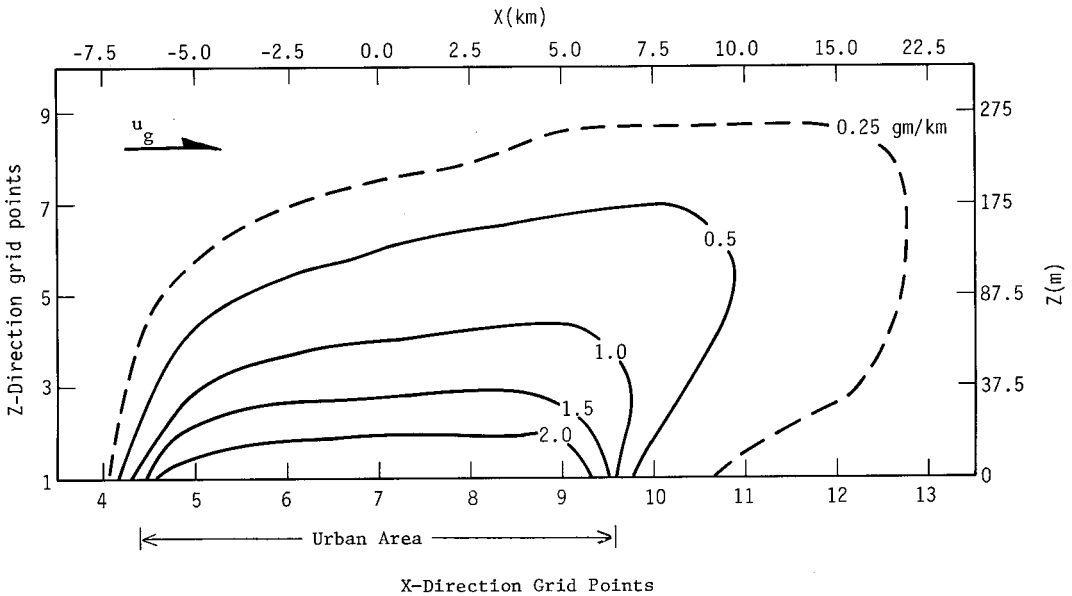
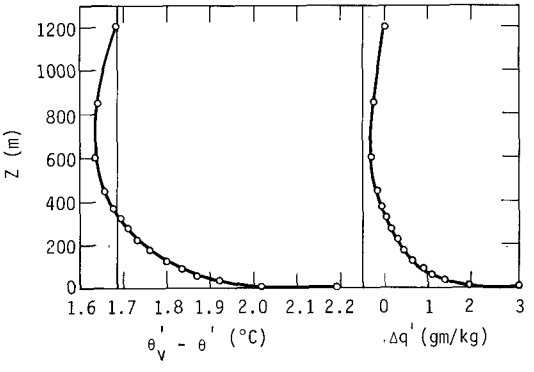


Figure 7.—Vertical variation of $\Delta q'$, the difference between the values of q' over the downwind urban edge and those at the upwind model edge, at 0600 LST for the run discussed in figure 6. Also shown is the vertical variation of θ_v'-θ' at the upwind model boundary (thin vertical line) and at the downwind urban edge (thick curve).



The excess moisture thus placed into the urban atmosphere was advected and diffused vertically and/or horizontally, as expressed by equation 7. A typical distribution of q' after 12 hours of simulated time at 0600 LST (fig. 6) shows the effects of the advection and diffusion.

The vertical variation of the difference between the values of the perturbation specific humidity q' over the downwind urban edge and those at the upwind model edge at 0600 LST (the righthand half of figure 7) produces a buoyancy effect, as wet air is less dense than dry air. This enhances the buoyancy produced by the urban heat-island effect. At the same height above the surface, the magnitude of the buoyancy produced by the urban moisture excess at any point is given by the difference between the value of $\theta'_v - \theta'$ at the upwind model boundary and that at the point (fig. 7). From these values, and from the values of the total predicted buoyancy due to the heat-island effect was computed. The results (table 10) indicate that, near the surface, the additional buoyancy due to the moisture excess is about 10 percent of that due to the heat-island effect.

However, observations of the moisture excess over New York City by Bornstein *et al. (1972)* indicate that the moisture excess of the urban atmosphere in the present simulation could be increased by a factor of two. Even with the amount of anthropogenic moisture currently specified, there is a noticeable increase in the magnitude of the urban breeze effect (fig. 8) at the center of the urban area. The maximum increase of ΔU in the case of an urban moisture excess (case 2) over those from the case of no urban moisture excess (case 1) is about 8 cm sec^{-1}, or about 15 percent.

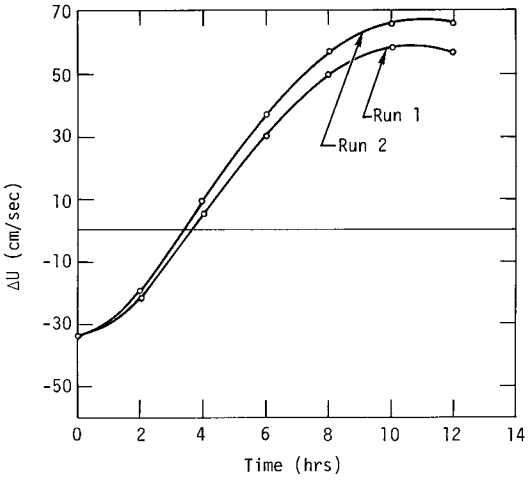
SUMMARY

A heat and moisture excess over of New York City has been shown to exist by use of helicopter soundings of temperature and wet-bulb depression. For three early morning flights, the moisture excess was about 0.9 gm m^{-3}, which represented an increase of about 10 percent over values at nearby rural sites. The humidity and moisture excesses were generally highest over the central part of the city, and then decreased over the peripheral urban areas, implying the existence of a heat and moisture dome over New York City.

Table 10.—Height variation of the temperature difference due to the urban moisture excess $\Delta\theta_1$, and due to the urban heat island $\Delta\theta_2$, at a site located at the downwind urban edge.

z (m)	$\Delta\theta_1$ (°C)	$\Delta\theta_2$ (°C)
0	0.5	5.8
12.5	.3	4.7
37.5	.2	2.5
67.5	.2	2.0
87.5	.1	1.7
125.0	.1	1.4
175.0	.1	1.0
225.0	.1	.8
275.0	.0	.7
325.0	.0	.6
375.0	.0	.4
450.0	.0	.3
600.0	.0	.1
850.0	.0	.0

Figure 8.—Time variation of the horizontal wind speed at a height of 125 m. Values represent the differences in cm sec^{-1} between the values at the upwind model boundary and those at the downwind urban edge for the two cases discussed in the text. The values of u_g and z_o are those given for figure 6.



The magnitude of the temporal and spatial distributions of anthropogenic moisture emissions in New York City from fixed and mobile area sources were estimated using fuel-use data collected during the NYU/NYC urban air-pollution dynamics project of 1964-69. The maximum annual emission rate from a particular square mile in Manhattan was found to be equal to about 25 percent of the annual evaporation rate in the coastal Atlantic off of New York City.

The URBMET urban boundary-layer model was used to evaluate the effects on the dynamics of the urban boundary layer resulting from the buoyancy associated with an observed urban moisture excess. Results indicated that the buoyancy produced by the moisture excess was about 10 percent of that produced by the urban heat-island effect. This excess buoyancy enhanced the strength of the urban-breeze effect by about 15 percent over what had resulted due to the heat-island effect alone.

Work is currently in progress to determine the fraction of the observed nighttime moisture excess over New York City that is due to each of the following: area-source emissions of moisture, point-source emissions of moisture, and reduced nighttime condensation rates in the urban areas, as compared to those in nearby rural areas. In this work, the flux of anthropogenic moisture into the atmosphere is used as a surface boundary condition for the URBMET boundary-layer model.

There is no completely satisfactory method of incorporating area and point-source emissions of moisture into a boundary-layer model. In previous models area sources of heat have been included in surface energy balances, even though some of this energy enters the atmosphere through the sides and tops of buildings. In addition, point sources cannot be represented in two-dimensional finite difference boundary-layer models, which can only treat line and area sources. Thus work remains to be done in order to accurately represent the effects of anthropogenic heat and moisture on the structure of the urban boundary layer.

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LIST OF SYMBOLS

Variables and Constants—Roman Alphabet

$a(x,t)$	Specified variation of the surface specific humidity
h	Top of constant flux layer, equal to 25 m
H	Top of transition layer, equal to 1900 m
i	Horizontal index for horizontal wind and temperature grid
j	Vertical index for horizontal wind and temperature grid
K	Generalized eddy transfer coefficients in $cm^2\ sec^{-1}$
K_H	Eddy transfer coefficient for heat in $cm^2\ sec^{-1}$
K_q	Eddy transfer coefficient for moisture in $cm^2\ sec^{-1}$
M'_A	Annual emission of moisture from a particular area source, in gm per year
M_A	Same as M'_A, but in gm $cm^{-2}\ sec^{-1}$
M_D	Daily emission of moisture from a particular area source grid, in gm $cm^{-2}\ sec^{-1}$
M_i	Moisture emission factor for the i-th fuel
p	Atmospheric pressure in dynes cm^{-2}
p_m	Constant space average of pressure in dynes cm^{-2}
p_o	Variation of pressure in absence of perturbation motion in dynes cm^{-2}
p'	Fluctuation of pressure due to perturbation motion in dynes cm^{-2}
P_i	Percent of total SO_2 emission in a grid from use of the i-th fuel
q	Specific humidity in grams of moisture per grams of moist air

q_m, q_o, q'	See pressure definitions
q^*	Friction specific humidity in grams of moisture per grams of moist air
S_i	SO_2 emission factor for i-th fuel
t	Time in sec
T	Temperature in K
T_m, T_o, T'	See pressure definitions
u	Horizontal component of wind in the x-direction in cm sec^{-1}
u_g	Geostrophic wind in x-direction in cm sec^{-1}
u^*	Friction velocity in cm sec^{-1}
U	Total horizontal wind speed in cm sec^{-1}
v	Horizontal component of wind in the y-direction in cm sec^{-1}
w	Vertical component of the wind in cm sec^{-1}
x	Horizontal coordination in direction of geostrophic wind in cm
y	Horizontal coordinate in direction perpendicular to the geostrophic wind in cm
z	Vertical coordinate for vorticity in cm
z_o	Aerodynamic roughness length in cm

Variables and Constants—Greek Alphabet

Γ	Dry adiabatic cooling rate, equal to 9.8 K km^{-1}
ζ	Modified y-component of vorticity in sec^{-1}
θ	Potential temperature in K
θ_m, θ_o, θ'	See pressure definitions
θ_v	Virtual potential temperature in K
θ'_v	Perturbation virtual potential temperature in K
θ^*	Friction potential temperature in K
Ψ	Stream function in cm^2 sec^{-1}
Δ	Difference operator

Acknowledgments. Part of this research was conducted using the facilities of the Atmospheric and Geophysical Sciences Division of Lawrence Livermore Laboratory under the auspices of the U.S.E.R.D.A. Part of the work was also supported by National Science Foundation grant No. GA-41886 and by U.S. Environmental Protection Agency grant No. DU-74-B491 to the Department of Meteorology at San Jose State University.

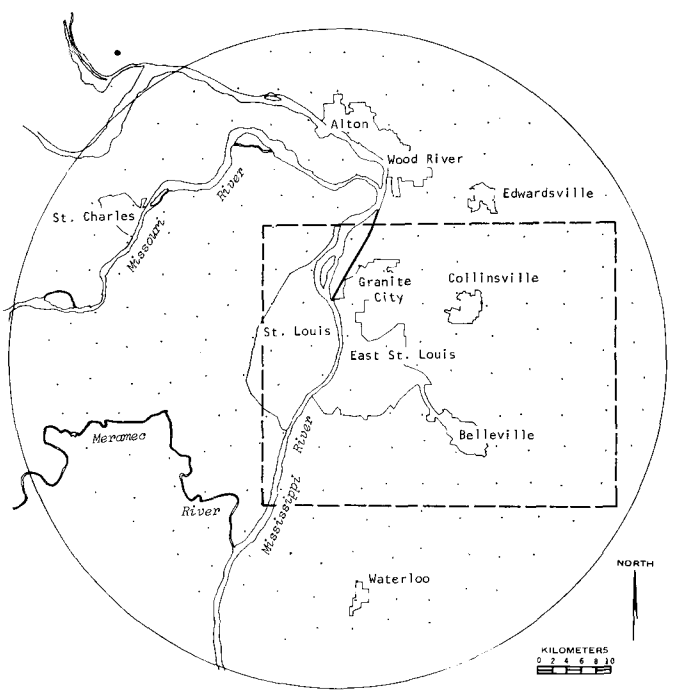
Temporal and Spatial Variability of Rainfall pH

by RICHARD G. SEMONIN, *assistant head, Atmospheric Sciences Section, Illinois State Water Survey, Urbana, Ill.*

ABSTRACT.—The distribution of average rainwater pH over an area of 1,800 km^2 containing 81 collectors was determined from 25 storm events. The areal average of the data was pH 4.9, with a range of values from 4.3 to 6.8. A single storm event was studied to determine the change of pH as a function of time. The initial rain was pH 7.1, decreasing to 4.1. An excellent agreement was observed between the H^+ deposition rate and the rainfall rate.

THE STUDY OF PRECIPITATION chemistry is an essential component of the METROMEX (METROpolitan Meteorological EXperiment) research on inadvertent weather modification at St. Louis, Mo. Through the use of chemical tracers and analytical techniques, it has been established *(Semonin 1972)* that materials released from near the surface are processed, scavenged, and deposited by migratory storm systems in an area defined in climatological studies of Huff and Changnon *(1972)* as the St. Louis precipitation anomaly. The chemistry research is directed toward the estimation of convective cloud scavenging efficiency by the analysis of several elements found in rainwater, but also includes the occasional measurement of pH and conductivity.

Figure 1.—The St. Louis METROMEX field project research area. The dashed rectangle delineates the precipitation chemistry network.



Much of the land area within the METROMEX research circle (fig. 1) is in agriculture, and the deposition of the hydrogen ion in a localized high-rainfall area is a feature of inadvertent weather modification pertinent to crop production in proximity to urban centers. In addition, the effect of pH on the quality of storm runoff water and shallow groundwater supplies is a subject requiring serious attention as continued industrial development proceeds.

The data presented here begin to address these problem areas by illustrating the local variability of precipitation pH. An evaluation of the impact of such pH variability on regional planning, crop production, and local water supplies is treated. Though these impacts are extremely important, the nearly total lack of validation of rainwater pH effects on agriculture and water quality relegate this paper to presenting data with little interpretation of its meaning to longer-range problems of environmental quality.

DATA COLLECTION

Twenty-five convective storm days in the summers of 1972 and 1974 comprise the data set. The area studied covers 1,800 km^2 and contains a network of 81 rainwater collectors and 3 sequential rain samplers described by Gatz et al. *(1971)*.

The network samplers consist of a 1-liter polyethylene bottle fixed to a metal farm fencepost by an adjustable large-diameter hose clamp. The samples were collected within 2 hours after cessation of precipitation and transported to the laboratory facility for analysis within 36 hours. The pH was determined immediately upon arrival of the sample in the laboratory and before any preparations for subsequent elemental analysis by atomic absorption spectrophotometry.

The sequentially collected samples were treated in the same way as those from the network. However, these samples were acquired as a function of rainfall rate by a tipping-bucket arrangement in a housing containing 72 collector bottles. The bucket emptied into polyethylene bottles after sufficient volume of rain fell on the 1-m^2 collection surface (usually ½ liter), and the local time was recorded for each collection event. The recorded time interval for the sample collection was used to calculate the rates of deposition for the precipitation, various elements, and the hydrogen ion.

AREAL VARIABILITY

The pH determinations from each site for all 25 storm events were combined to provide an average distribution over the sampling network. The average pH values were calculated by first computing the total grams of hydrogen ion deposited by the 25 storms and dividing by the total water collected. The results (fig. 2) show that it is difficult to envision a direct relationship between known SO_2 sources (fig. 3) and the areal pattern of the pH.

The area of pH $\leqslant$ 4.5 can, of course, be qualitatively related to the concentration of point sources along the Mississippi River in St. Louis and E. St. Louis. Likewise, the small area of pH $\leqslant$ 4.5 near Granite City coincides with the indicated nearby sources. However, the large areas of pH $\geqslant$ 6.5 over the St. Louis urban center, and the low pH values in the southeastern corner of the network do not correlate well with known industrial operations. The overall average pH for the entire 1,800-km^2 area determined by combining the measurements for all storms from all sampling sites was 4.9

An examination of the frequency of pH $\leqslant$ 4.5 (fig. 4) was made to determine the persistance of low pH values at each site. The high frequency in the southeastern corner of the network remains an anomaly and requires verification by additional data. The remaining centers of frequent occurrence can be attributed to SO_2 sources in proximity.

Figure 2.—The rainfall-weighted average pH pattern derived from 25 storms. The areal mean is 4.9 with a range of values from 4.3 to 6.8.

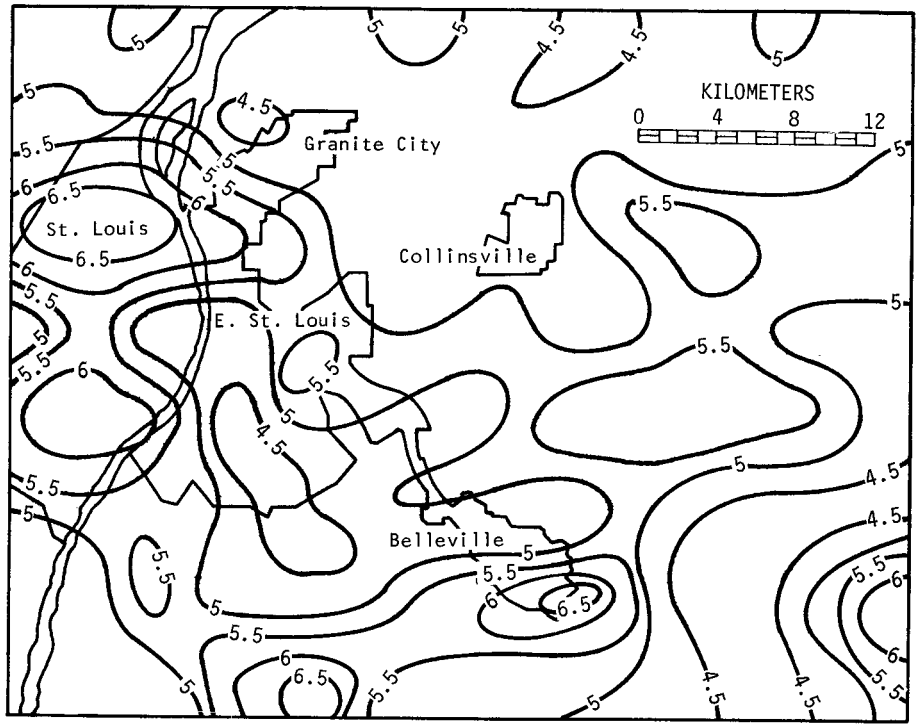


Figure 3.—The location and estimated sulfur oxide source strength in proximity to the chemistry network.

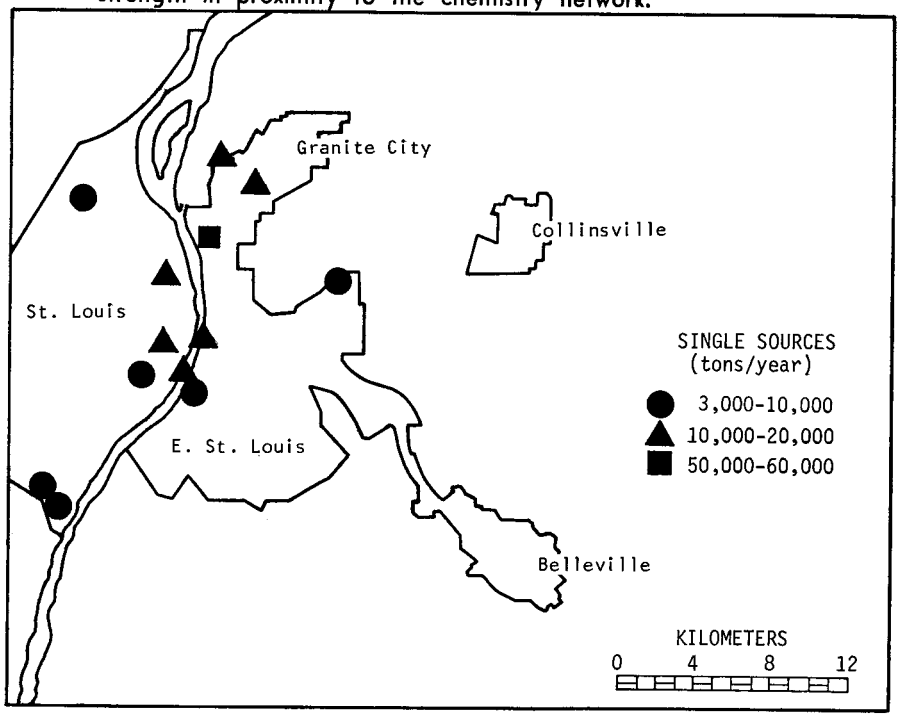
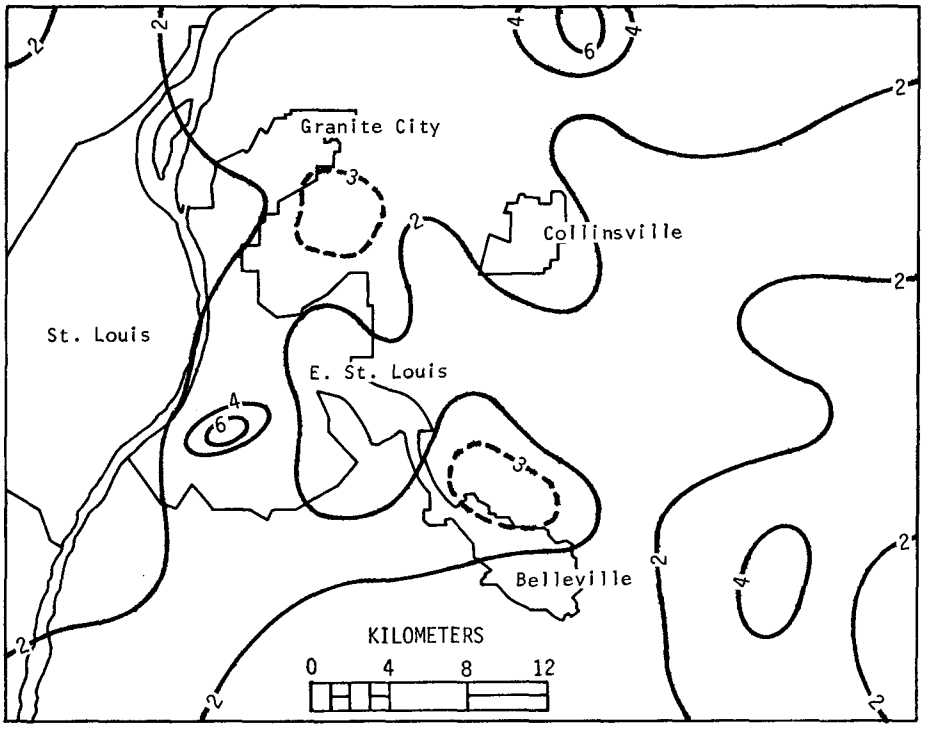


Figure 4.—The point frequency of pH $\leqslant$ 4.5 from the 25 storm data set.



The value near Edwardsville may be due to the Wood River refineries 10 km northwest of the network. It is interesting to note that only 15 to 25 percent of the rain samples in these areas produced the average pH values $\leqslant$ 4.5.

The average rainwater (fig. 5) associated with the 25 storm events is consistent with the concept of inadvertent precipitation modification by an urban complex. The historical records for the St. Louis region indicate a rainfall anomaly extending north to south approximately 15 to 25 km east of the Mississippi River. Even the small sample of storm events used for this study indicates an average high rainfall in the anomaly area, which points to the problems of selecting data-collection sites.

The hydrogen ion deposition (fig. 6) calculated from the pH and rain volume shows somewhat better spatial correlation with the SO_2 sources. However, the removal processes by convective storms are extremely complex and variable, resulting in a spatial averaging and smoothing of the observed rainfall and pH data. The results from METROMEX *(Huff 1973)* indicate two major areas of importance to inadvertent precipitation modification. The first of these is the city of St. Louis; the second is the Alton-Wood River industrial complex. The latter is not included within the network boundaries, and the contribution of Alton-Wood River to the pH variability can only be surmised at this time.

The deposition pattern can be envisioned as consisting of three bands of relatively high deposition oriented approximately north to south and separated by 15 to 20 km. Though this orientation is not unlike that of organized convective storm systems, there is no meteorological explanation for the apparent banded structure of deposition. A superficial comparison between the patterns of average rainfall (fig. 5)

Figure 5.—The average rainfall from the 25 convective storms used in this study, in milliliters.

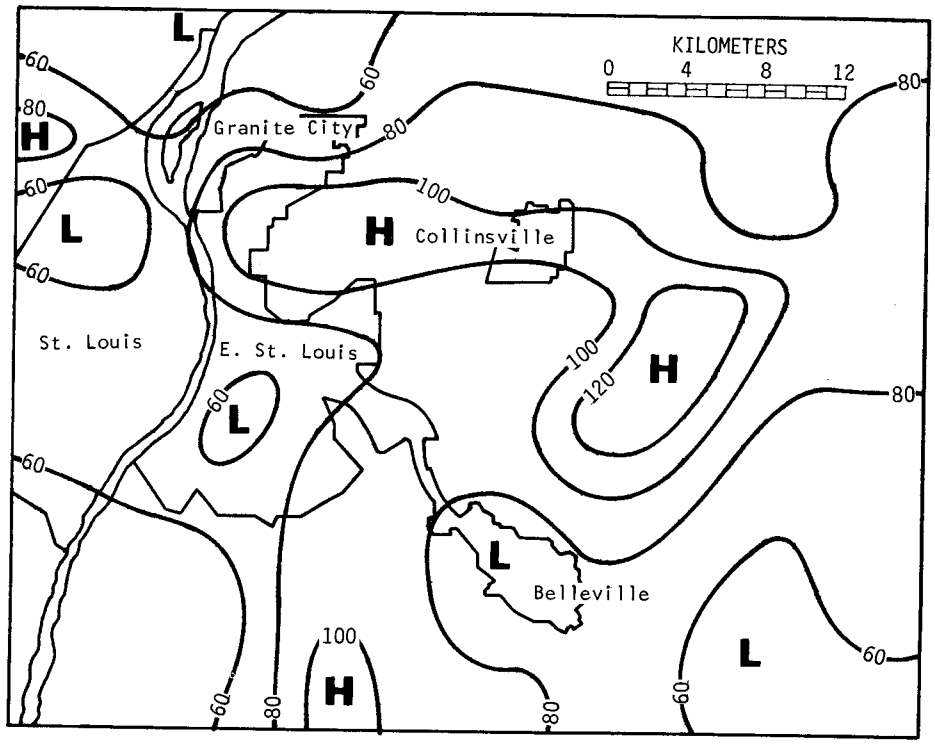


Figure 6.—The average H^+ deposition calculated from the rainfall and pH measurements, in micrograms.

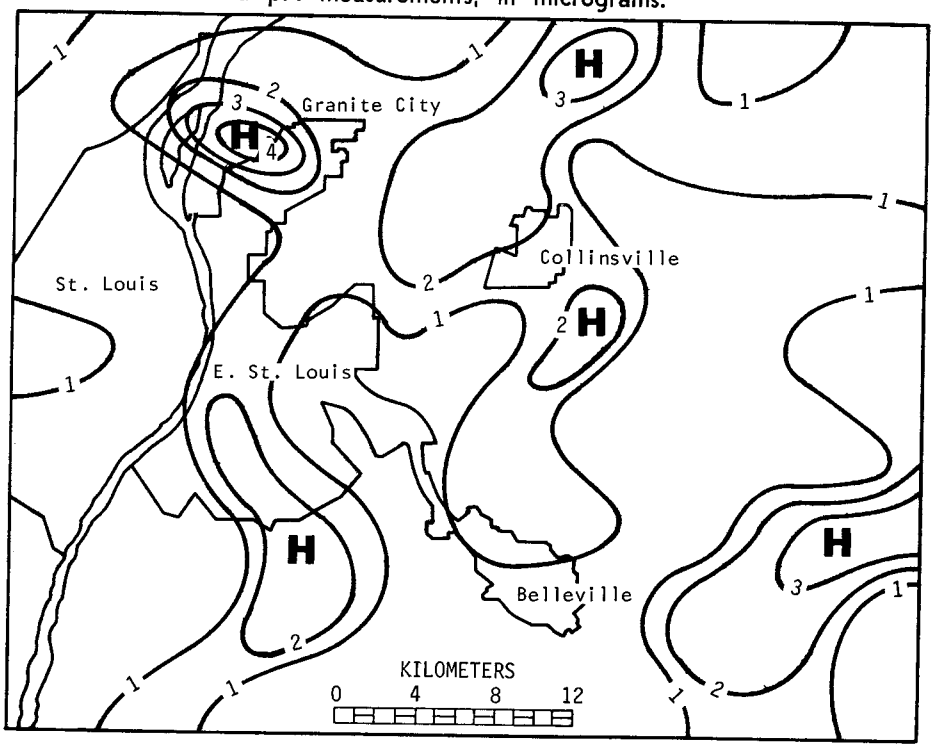
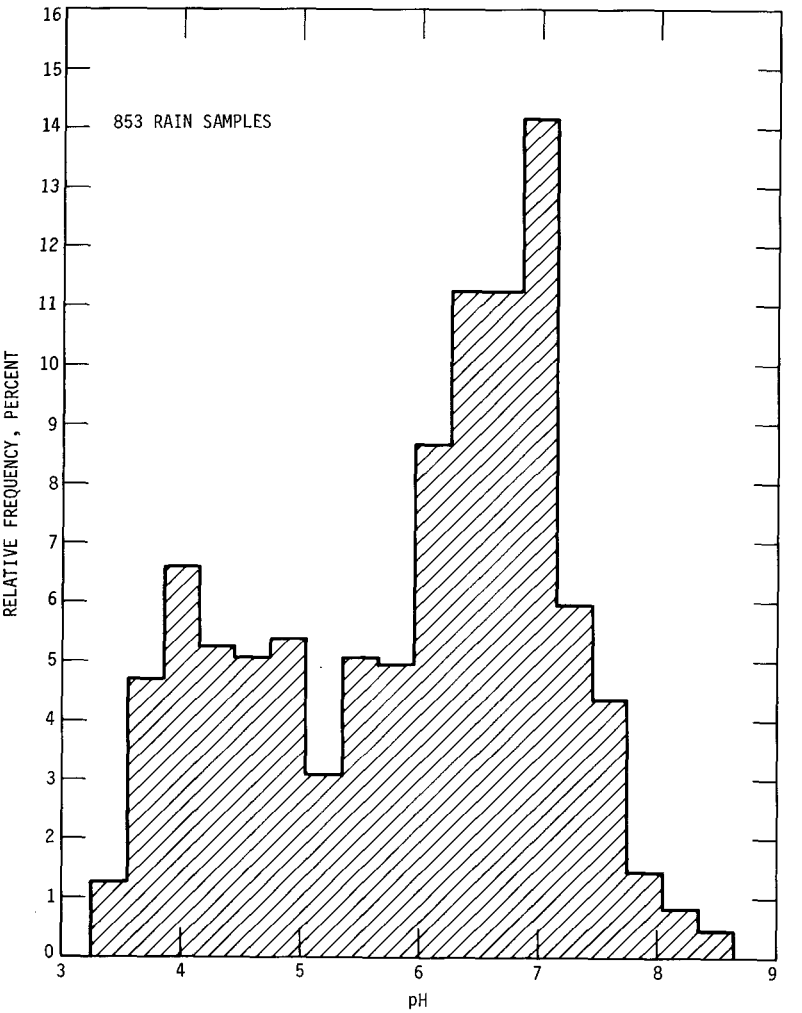


Figure 7.—The relative frequency distribution of rainwater pH from 25 storms in 1972 and 1974.



and average pH (fig. 2) suggests little correlation and emphasizes the independence of these two variables. Consequently, it is necessary to measure both the total rainfall and the pH to assess the potential environmental response to acid rainfall.

The relative frequency of pH (fig. 7) obtained by combining all 853 observations from the network is another way of illustrating the variability of acid rainfall. The most striking feature of this analysis is the high frequency of neutral rainfall and the secondary peak at 4.2 pH. This secondary peak is created by the relatively few sites that undergo frequent low pH precipitation as previously described. Further measurements are necessary, however, to determine the precipitaton pH frequency in other seasons of the year when urban and industrial emissions may be quite different from those during the summer months.

TEMPORAL VARIABILITY

The potental impact of pH on the environment cannot be fully determined by study of bulk rain samples as acquired from the network. For example, all the

pH-determining compounds could be deposited either at the beginning or at the end of a convective storm, with different implications as to the expected effects.

The data obtained on 3 August 1972 exemplify the temporal change of pH and the changes of rainfall rate (fig. 8). Throughout the first 45 minutes of rain the pH decreased dramatically from 7.1 to 4.1 while the rainfall rate remained relatively constant between 1 and 7mm hr^{-1}. The independent, nearby total rain sample had a pH of 3.9. Apparently the high pH of the initial light rain was insufficient to neutralize the later more intense and more acid precipitation.

The measurements from other storm events show opposite temporal change of pH; that is, increasing from low values to relatively constant values. This is an important feature of precipitation deposition of materials, making it possible to estimate the time rate of change of deposition. Since the concentration approaches a constant shortly after the initiation of a storm event at a point, the variation of the deposition rate is directly related to the preciptation rate (fig. 9). Therefore, as a first approximation for the depiction of the rate of hydrogen ion deposition, simple measurements of total storm rainfall pH and rainfall rate are all that is required.

SUMMARY AND DISCUSSION

The areal variability of average pH appears to be independent of the average rainfall variability and cannot be related easily to known SO_2 sources. With the exception of a few sites, the

Figure 8.—The variation of pH (closed circles) with time during the convective storm of 3 August 1972. The nearby total storm sample pH of 3.9 is indicated by the horizontal line. The rainfall rate (open circles) in millimeters per hour is shown for reference.

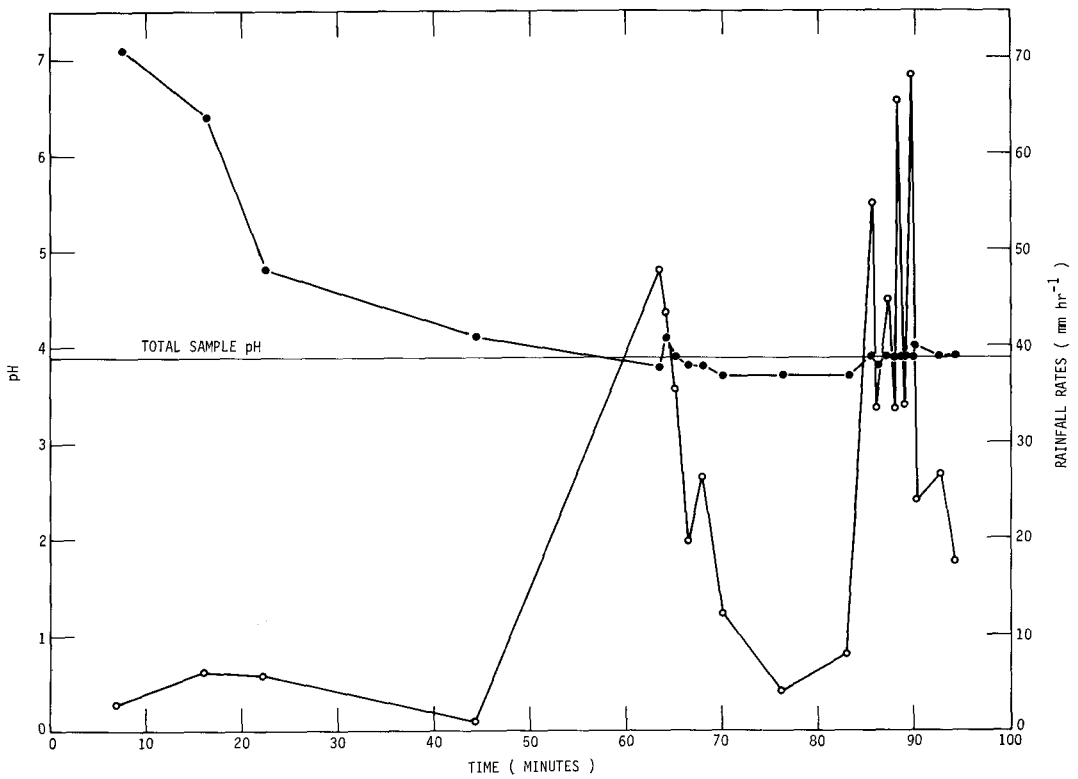
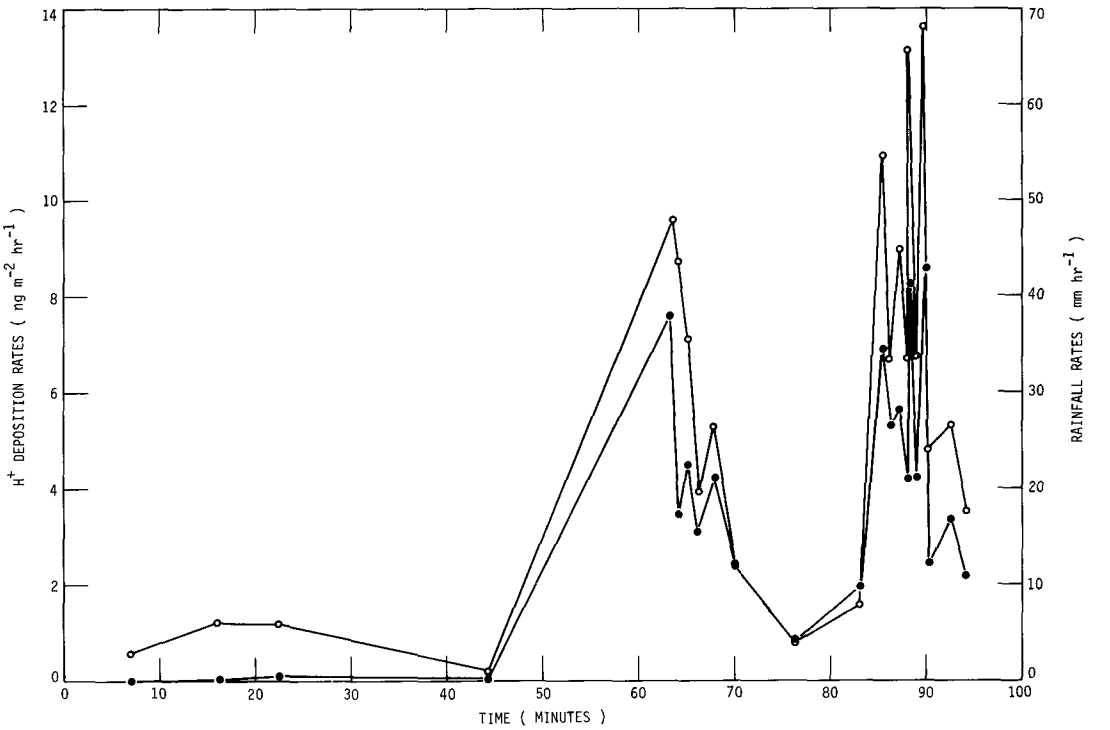


Figure 9.—The H^+ deposition rate (closed circles) and rainfall rate relationship for the storm of 3 August 1972.



most frequently observed pH was 7.0, indicating that acid rainfall is not an extremely serious problem in the 1,800-km^2 area immediately east of St. Louis. These data do point out the difficulties with regard to point measurements, and suggest that any conclusions regarding long-term trends must be viewed cautiously. The average pH may vary from an acid value ($\leqslant$ 4.0) to an alkaline value over a distance of a few kilometers.

The study of the temporal change of pH in convective precipitation further complicates the assessment of the variability. The case study presented showed a three-unit change of pH during the initial 45 minutes of a storm, with little subsequent change. During the period of nearly constant pH, the rainfall rate varied rapidly throughout the storm duration.

The observations reported here illustrate certain problems that must be treated in discussions on acid rainfall. The first is related to the desired use of the data. For the study of precipitation chemistry without regard to environmental impact, the long-term monitoring of pH from a single site may be acceptable. However, when the ultimate utility of pH data for the soil scientist, water quality expert, agriculturalist, and many other potential users is considered, these data show that single-site observations can lead to erroneous relationships between environmental degradation and precipitation.

The second problem area addressed in this paper is the relationship between the time-varying and total storm rainwater pH. The measurements show variations of pH during the storm to be as large as the spatial variations. Therefore, the study of the response of the environment to the acid content of precipitation must carefully consider such wide variations both in space and time.

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Acknowledgments. The work reported here was funded by ERDA Contract E(11-1)-1199 as part of the METROMEX research program. The author is indebted to M. Peden and A. Rattonetti for their diligence and care in performing the pH determinations.

Effect of Urbanization on the Thermal Structure in the Atmosphere

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ABSTRACT.—An unsteady two-dimensional transport model was used to study the short-term effects of urbanization and air pollution on the thermal structure in the urban atmosphere. A number of simulations for summer conditions representing the city of St. Louis were performed. The diurnal variation of the surface temperature and thermal structure are presented and the influences of various parameters are discussed.

IT IS ESSENTIAL in air-pollution forecasting to understand how urbanization and the urban area modify the atmospheric environment not only in the immediate vicinity of the city, but also for a considerable distance downwind. Modification of the environment takes on many forms and includes alteration of the wind, temperature, and water-vapor profiles as well as the surface temperature and the injection of gaseous and particulate pollutants into the atmosphere.

During the past few years, many serious atempts have been made to observe and explain the microclimatic effects over and around urban areas. The best-documented and least-questioned climatic effect is the urban influence on temperature in the atmosphere. The urban heat-island phenomena is clearly a result of the modification of surface and atmospheric parameters by urbanization, which in turn leads to an altered energy balance. The possible causes of the heat island are well recognized *(Peterson 1969)*, but the individual effects such as physical and radiative property differences between urban and rural areas, flow changes caused by the roughness elements, man-made heat sources and radiatively participating pollutants have not been sufficiently studied, and their quantitative influences are not completely understood.

Observational programs and mathematical modeling are needed to gain understanding of the urban environment. Unfortunately, the very nature of the urban environment necessitates extensive measurements over large distances and long periods of time, which are not only difficult but also costly. Therefore mathematical models can be employed to advantage to help fill the observational gap by numerically simulating the transport processes in the atmosphere. To the extent that the mathematical model simulates the real atmosphere, it can then become a valuable tool for use in micrometeorological weather prediction, forcasting of pollution episodes, urban planning, interpretation of field data, and identification of pollutants by means of remote sensing methods.

In addition to the above, numerical simulations can also be used as a guide for observational programs such as the Regional Air Pollution Study (RAPS) sponsored by the U. S. Environmental Protection Agency (EPA) for the St.

Louis Metropolitan area. The main advantage of a numerical simulation lies in its ability to predict what will happen for any given changes in urban parameters, boundary, or initial conditions.

In this paper we will describe the short-term effects of urbanization on the thermal structure in the atmosphere of an urban area, using an unsteady two-dimensional transport model. The emphasis is on the potential effects of urbanization and air pollution on the thermal structure in the urban planetary boundary layer. As a specific example, results of numerical simulations of the city of St. Louis for summer conditions are discussed. Results of similar experiments have been reported *(Pandolfo et al. 1971, Atwater 1972, Bornstein 1972, Wagner and Yu 1972,* and *Atwater 1974).*

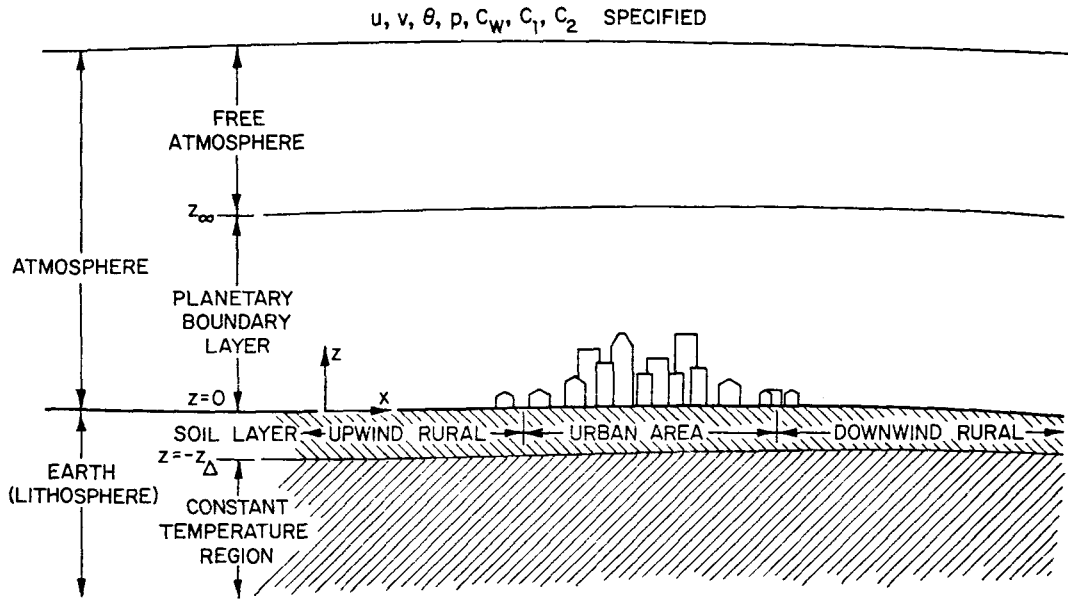
NUMERICAL MODEL

Physical Model and Assumptions

In the unsteady two-dimensional transport model (fig. 1), the earth-atmosphere system is assumed to be composed of four layers: (1) the free (natural) atmosphere where the meteorological variables are considered to be time-independent; (2) the polluted atmosphere (the planetary boundary layer, PBL), where the meteorological variables such as the horizontal, vertical, and lateral wind velocities, temperature, water vapor, and pollutant concentrations are functions of time, height, and distance along the urban area; (3) the soil layer, where the temperature is assumed to be a function of depth and time only (the soil and interfacial radiation properties are allowed to vary in the horizontal direction); and (4) the lithosphere, where the temperature is assumed to be constant during the simulation period. The atmosphere is assumed to be cloud-free, and no variation of topography is accounted for along the urban area.

In the polluted urban planetary boundary layer the transport of momentum, energy, and species takes place by vertical and horizontal advection as well as by vertical and horizontal turbulent diffusion. In addition, radiative energy is transported in the solar (short-wave)

Figure 1.—Schematic representation of the urban environment and of influences analyzed by the urban boundary layer model.



and thermal (long-wave) portions of the spectrum. The interaction of both natural atmospheric constituents and gaseous as well as particulate pollutants with solar and thermal radiation is accounted for. The planetary boundary layer and soil layer are coupled by energy and species balances at the atmosphere-soil interface. The horizontal variation of the urban parameters such as man-made heat and pollutant sources, surface solar albedo (reflectance) and thermal emittance, surface roughness, thermal diffusivity and conductivity of the soil, and Halstead's soil moisture parameter are arbitrarily prescribed functions of position along the urban area. It has been observed *(Stern et al. 1972)* that the man-made heat and pollutant sources, for example, vary during the diurnal cycle. However, more realistic modeling of these sources during the diurnal cycle must await more complete observational data.

Model Equations

The numerical model is based on the conservation equations of mass, momentum, energy, and species. The equations used to describe the planetary boundary layer can be written in a general form as

$$\frac{\partial \phi_i}{\partial t} + u\frac{\partial \phi_i}{\partial x} + w\frac{\partial \phi_i}{\partial z} = \frac{\partial}{\partial x}\left(K_{xi}\frac{\partial \phi_i}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_{zi}\frac{\partial \phi_i}{\partial z}\right) + S_i(x,z,t) \qquad [1]$$

where t, x, and z are the time, horizontal, and vertical coordinates; u and w are the horizontal and vertical velocity components; $\phi_i(x,z,t)$ is the dependent variable "conserved;" $S_i(x,z,t)$ is the appropriate source term; and K_{xi} and K_{zi} are suitable turbulent diffusivities. The independent variables and their corresponding sources are listed in table 1. A general discussion of the conservation equations was given by Plate *(1971)*, and Johnson *(1975)* presented a detailed derivation of the equations used in the model.

The boundary conditions prescribed at the edge of the outer flow (top of the PBL) and at the soil surface are the following: at the edge of the outer flow, ϕ_i is specified; at the interface, u = v = w = 0; and the surface temperature (at any x) is predicted from an energy balance

$$[1 - r_s(x)]F_s(x,0) + e_t(x)F_t(x,0) - e_t(x)\sigma T^4(x,0) + \left(k + \rho c_p K_z^{\theta}\right)\left.\frac{\partial \theta}{\partial z}\right|_0 + L\rho\left(D_w + K_z^{C_w}\right)\left.\frac{\partial C_w}{\partial z}\right|_0 - k_g(z)\left.\frac{\partial T_g}{\partial z}\right|_0 + Q = 0 \qquad [2]$$

In this equation, the first two terms account for absorption of solar and thermal radiation, the third term represents thermal emission, the fourth and fifth terms account for sensible and latent heat transfer by molecular and turbulent diffusion, the sixth term rep-

Table 1.—Dependent variables and source terms

	ϕ_i		S_i
1	u	horizontal velocity	$f(v-v_g)$ geostrophic deviation
2	v	lateral velocity	$f(u_g-u)$ geostrophic deviation
3	θ	potential temperature	$\partial F/\partial z$, q radiative and man-made heat sources
4	C_w	water-vapor concentration	$\dot{C}_w$ water vapor emission
5	C_1	concentration of pollutant aerosol	$\dot{C}_1$ pollution emission
6	C_2	concentration of gaseous pollutant	$\dot{C}_2$ pollution emission

resents heat conduction into the ground, and the final term is the man-made surface heat flux. The water vapor concentration at the surface is prescribed by Halstead's moisture parameter *(Pandolfo et al. 1971)* by the expression

$$C_w(x,0) = M(x)\,C_{w,sat}[T(x,0)] + [1-M(x)]\,C_w(z_1,0) \quad [3]$$

where M is the moisture parameter, $C_{w,sat}$ is the water-vapor concentration at saturated conditions, and z_1 is the first grid point above the surface. For a prescribed pollutant flux at the surface, m_n, a species balance at the interface, yields the condition

$$m_n = -\left(D_n + K^{C_n}\right)\left.\frac{\partial C_n}{\partial z}\right|_0 \quad , n=1 \text{ and } 2 \quad [4]$$

At the upwind boundary, the meteorological variables are predicted from the unsteady one-dimensional model of Bergstrom and Viskanta *(1973a)*. Initially, ϕ_i is specified everywhere and is assumed to be independent of the horizontal coordinate x.

Turbulent Diffusivities

Specification of turbulent diffusivities for an urban atmosphere in connection with numerical modeling of the PBL is a very difficult task and has been discussed in a recent review *(Oke 1973a)*. The semi-empirical equations developed by Pandolfo et al. *(1971)* were initially employed. The decay of turbulence in the upper part of the PBL was prescribed by following Blackadar's *(1962)* formulation. However, in the hours before sunrise, when the atmosphere became quite stable, unrealistically deep surface inversions resulted and the Richardson numbers were found to exceed the critical value.

In these situations the diffusivities predicted by Pandolfo's eddy diffusivity-Richardson number correlations were not applicable. Therefore, the cubic polynomial developed by O'Brien *(1970)* and used by Bornstein *(1972)* was employed for the prediction of the diffusivities in the transition layer under stable conditions.

Stable conditions were assumed to exist when the average Richardson number in the lowest 25 m of the atmosphere was greater than zero. Where this condition was reached, Pandolfo's model was used only near the surface, while the polynomial was employed in the transition layer. Otherwise, Pandolfo's model was used throughout the entire PBL. If the Richardson number exceeded the critical value, it was reset to this value so that unreasonable diffusivity values would not be predicted.

Radiative Transfer Model

The radiative transfer model used has been discussed in detail elsewhere *(Bergstrom and Viskanta 1973b)*, so only a summary of it is included here. The urban atmosphere is considered to be cloudless, plane-parallel, and consisting of two layers: (1) the free atmosphere, and (2) the urban PBL where the pollutants are concentrated. The earth's surface was considered to emit and reflect radiation as prescribed functions of wavelength. Since the atmospheric gases and particles absorb, emit, and scatter radiation, the radiative transfer between the free atmosphere and the PBL is coupled. However, no consideration is given to individual point sources of pollutants. Since multidimensional radiative transfer is complex, it is assumed that the transport of radiation can be approximated by a quasi-two-dimensional field based on the vertical temperature, water-vapor, and pollutant distributions at several predetermined horizontal positions. The radiative fluxes in the atmosphere are then evaluated at a few prescribed horizontal locations and linear or nonlinear interpolation is then used to determine the radiative fluxes between these locations.

The radiative fluxes and flux divergences are evaluated by dividing the

entire electromagnetic spectrum into solar ($0.3 \leqslant \lambda < 4$ μm) and thermal ($4 \leqslant \lambda \leqslant 100$ μm) portions. The computational details can be found in Bergstrom and Viskanta *(1973b)*. Total emissivity data for water vapor and carbon dioxide were used, and scattering was neglected in predicting radiative transfer in the thermal part of the spectrum. It was assumed that the influence of gaseous pollutants could be confined to the 8 to 12 μm spectral region due to the relative opacity of the H_2O and CO_2 bands. Ethylene or sulfur dioxide were considered to be representative pollutants. The spectral absorption and scattering characteristics of the aerosol in a polluted atmosphere were taken from the model developed by Bergstrom *(1972)*.

Numerical Method of Solution

The alternating - direction - implicit (ADI) method *(Roache 1972)* was employed to solve the transport equations [1]. The selection of suitable grid spacing, appropriate finite-difference approximations for the spatial derivatives and the algorithm itself, and tests for convergence are discussed in detail by Johnson *(1975)*. To improve the resolution near the surface, a logarithmic-uniform grid spacing was chosen in the vertical direction. The logarithmic spacing extended to about 1 km from the earth surface, and from there to the top of the PBL (~ 2 km) the spacing was uniform. A uniform spacing was also employed in the horizontal direction and in the soil layer.

The number of grid points and their spacing in the vertical and horizontal directions can be varied. The results reported have been obtained by using 22 nodes in the vertical direction and 17 in the horizontal direction. The first vertical grid point was located at 5 m from the surface and the horizontal grid spacing was 1.5 km. The program required practically the entire high-speed memory capacity (138,000/150,000 bytes octal) of the National Center for Atmospheric Research CDC-7600 digital computer. The computational time was approximately 8 minutes for a 24-hour simulation period.

RESULTS AND DISCUSSION

Numerical Experiments

The numerical model has been tested, and a number of numerical experiments have been performed, using the city of St. Louis as an example. Because of the length and scope of the paper, it is possible to include only some selected results for the temperature in the atmosphere. The experiments were designed to simulate the thermal structure and pollutant dispersion in the urban atmosphere. The urban area was modeled by varying the appropriate surface parameters between rural and urban values in the horizontal direction. The value of these interface parameters are given in table 2. A horizontal distribu-

Table 2.—Numerical values of interface parameters for simulations (Johnson, 1975)

Parameter	Upwind rural	Urban Center
Solar albedo	0.18	0.12
Thermal emittance	.90	.95
Soil thermal conductivity (W/mK)	.1	.5
Soil thermal diffusivity (10^7 m^2/s)	1	2.5
Surface roughness (m)	.2	1.0
Moisture availability parameter	.1	.05
Lower soil boundary temperature (K)	295.5	295.5
Urban heat source (W/m^2)	2	20
Aerosol pollutant source ($\mu g/m^2s$)	0	2.5 or 5
Pollutant gas source ($\mu g/m^2s$)	0	2.5 or 5

tion was established by selecting the values of parameters at the rural and urban center locations and, for lack of any better data or information, a Gaussian distribution curve was then fitted between the urban and rural locations by specifying the standard deviation of a suitably chosen mean value. The data given in table 2 are representative values over the city.

The simulations were started at 1200 solar time and continued for a 24-hour period. The initial temperature profiles used were taken from Lettau and Davidson *(1957)* for 24 August 1954 and were imposed over the entire area (no x-variation). The initial horizontal and lateral velocity fields were either identical to or decreased by a factor of 2 of those given by Lettau and Davidson for the O'Neill Great Plains Turbulence Study. The pollutant-concentration profiles were initialized to a constant background value of 50 $\mu g/m^3$.

Components of the Energy Budget at the Surface

The surface temperature can be considered as the forcing function of the model. Thus it is important to understand the variation of the energy budget components along the urban area. These are presented in figures 2 and 3 at 2400 of the first day and 1200 of the second day. Inspection of figure 2 shows that the emitted (q_e) and the absorbed thermal (q_{at}) fluxes are the dominant components. The turbulent (q_t), the latent

Figure 2.—Variation of the surface balance flux components (q_t-turbulent, q_l-latent, q_e-emitted, q_{as}-absorbed solar, q_{at}-absorbed thermal, q_g-ground conduction, Q-urban heat source) at the surface at 2400 of the first day; Gaussian distribution, radiatively nonparticipating, u_g=6 m/s and v_g=4 m/s.

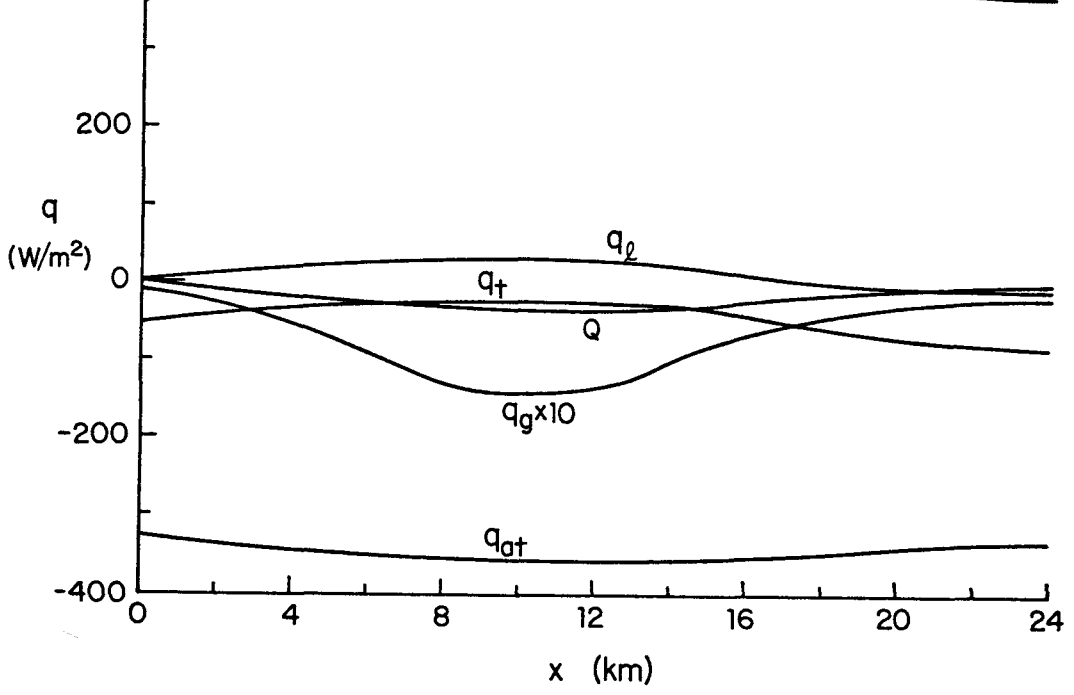
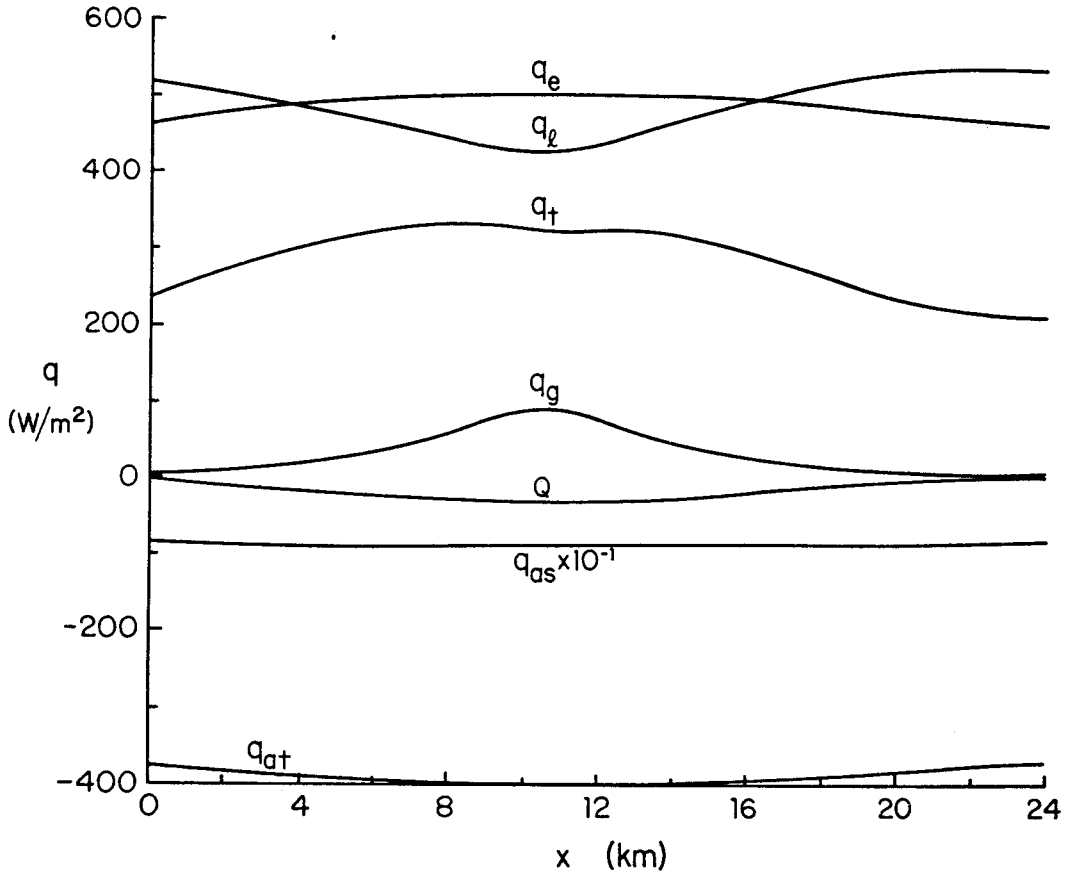


Figure 3.—Variation of surface energy balance flux components at 1200 of the second day; Gaussian distribution, radiatively nonparticipating, u_g=6 m/s and v_g=4 m/s.

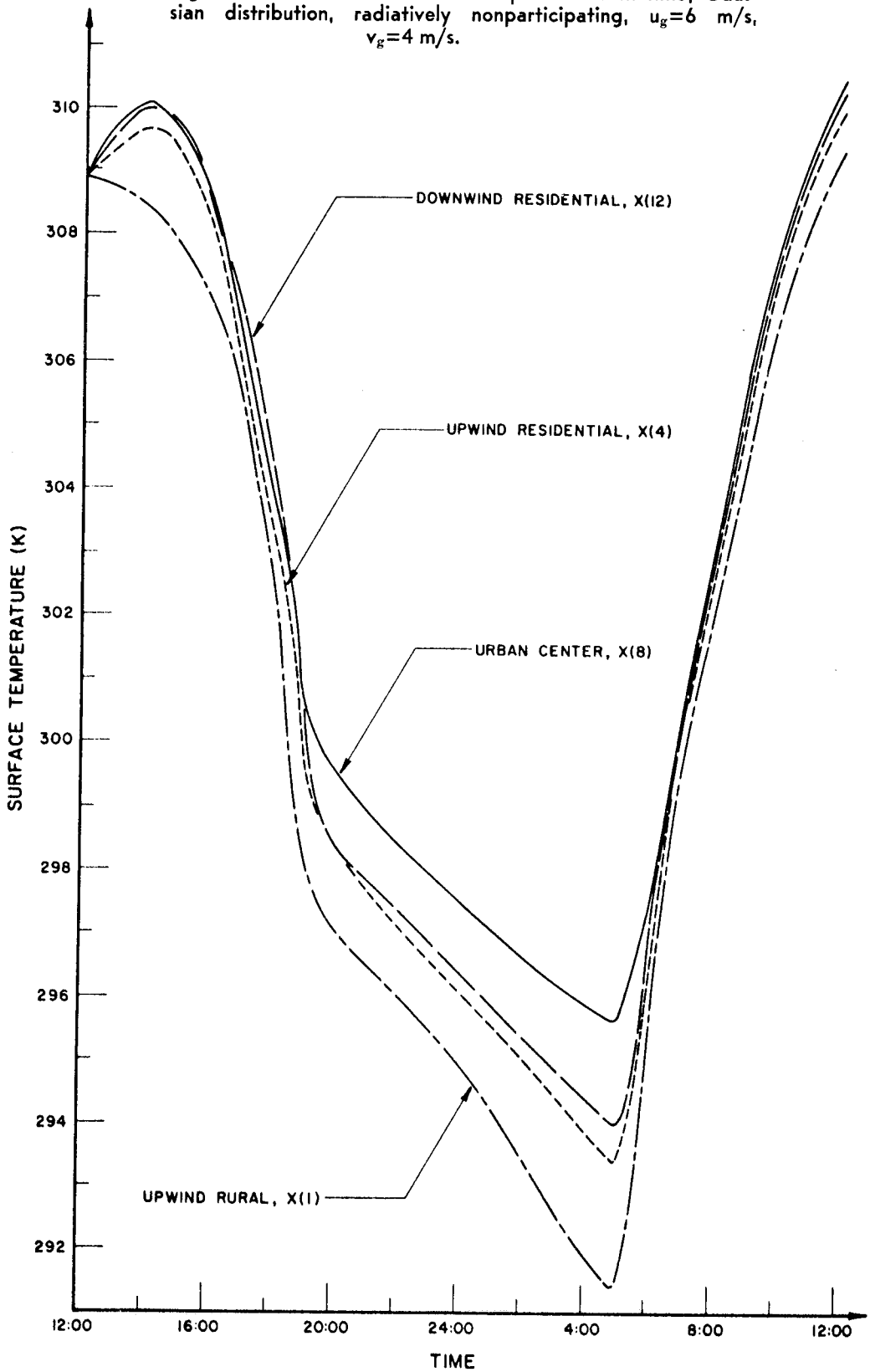


(q_l), the ground conduction (q_g), and the man-made urban heat (Q) fluxes are significantly smaller. However, at noon (fig. 3) the absorbed solar flux (q_{as}) is the largest term in the energy balance and the man-made heat source (Q) is the smallest. At the urban center (x = 10.5 km) the soil heat conduction term (q_g) amounts to only about 10 percent of the absorbed solar flux. The turbulent (q_t) and the latent (q_l) fluxes are quite sensitive to surface gradients and show significant variation along the urban area.

Surface Temperature

The diurnal variation of the surface temperatures at four positions along the urban area are shown in figure 4. The surface temperature drops sharply in the late afternoon, reaches a minimum just before sunrise (between 0500 and 0600), and rises sharply in the morning. During the first few hours of the simulation, an initial transient is noted in the surface temperature. This is due to the fact that the assumed initial velocity, temperature, and water-vapor concentration profiles were far away from the quasi-steady solution induced by the diurnal cycle, and it took about 2 to 3 hours for the system to adjust. The surface temperatures at the downwind residential location (node 12) are slightly higher than at the upwind residential (node 4) locations. This is attributed to the heating of the air as it flows over the warm city. The maximum surface

Figure 4.—Variation of surface temperature with time; Gaussian distribution, radiatively nonparticipating, u_g=6 m/s, v_g=4 m/s.



temperature difference (about 4°C) between the urban center and upwind rural locations occurs just before sunrise. On the other hand, for a simulation with higher wind speeds (u_g = 12 m/s and v_g = 8 m/s), the maximum difference occurs in the evening at 1900 and remains almost constant throughout the night *(Johnson 1975)*.

The effect of radiatively participating pollutants as measured by a local surface-temperature difference (temperature with participating pollutants/temperature without) is illustrated in figure 5. The temperature differences result from an interaction between many complex phenomena, and therefore individual influences are not easily identified. The surface temperature difference is largest during the night and reaches a maximum before sunrise 0500 and is smallest at noon. The differences between the surface temperatures are considerably smaller for higher wind speeds *(Johnson 1975)*.

A comparison of the surface temperatures for the Gaussian and rectangular distributions of urban man-made heat sources is illustrated in figure 6. The results show that the difference between the two results is only about 1°C, and the maximum occurs early in the morning (0500) when the man-made urban heat source is a significant component of the energy budget. At noon (1200) the surface temperatures in the city differ by only about 0.1°C, indicating the predominance of the radiant energy transfer in the interfacial energy balance.

Temperature Structure

The isopleths of the two-dimensional potential temperature fields at 6-hour

Figure 5.—Local surface temperature difference (simulation with radiatively participating pollutants minus simulation with radiatively nonparticipating pollutants) along the city; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, $m_1=m_2=2.5\ \mu g/m^2s$.

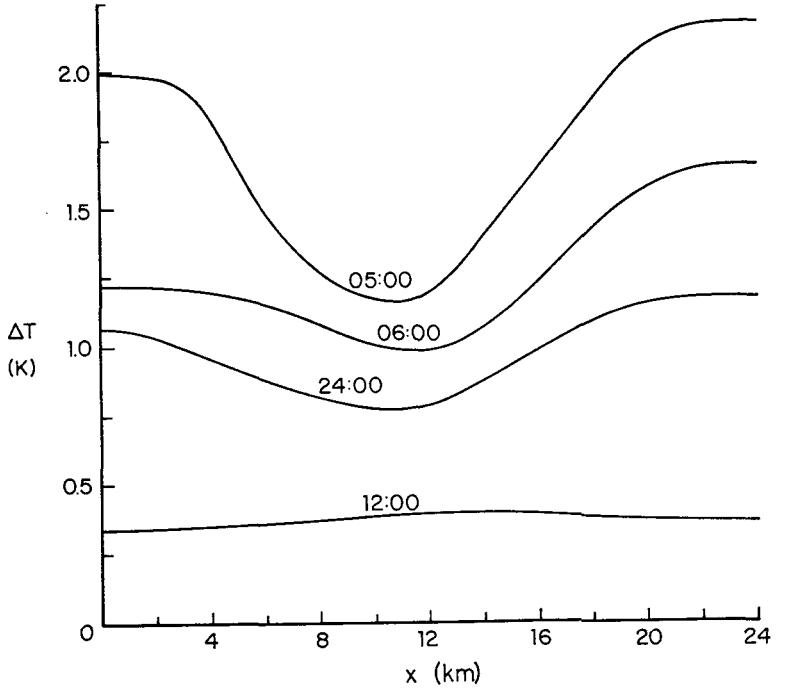
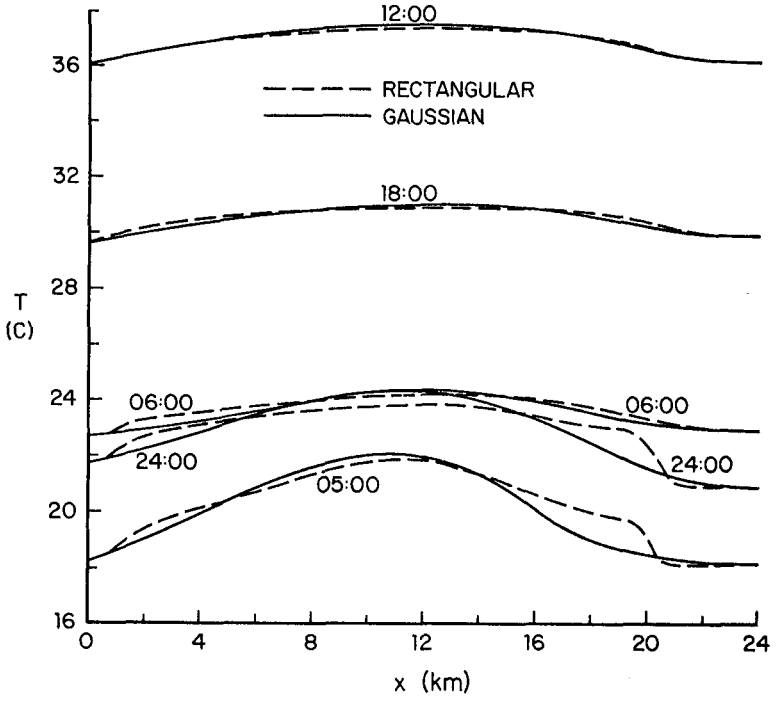


Figure 6.—Comparison of surface temperatures for Gaussian and rectangular distributions of urban heat and pollutant sources; radiatively participating, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, $m_1=m_2=2.5$ $\mu g/m^2s$.



intervals for a simulation with radiatively nonparticipating pollutants are shown in figure 7. At 1800 the atmosphere is nearly adiabatic, especially in the upwind rural area, with a thermal plume having a temperature of about 305 K forming at a height of about 100 m downwind of the city center (node 8, x = 10.5 km). Note that the last digit denoting the temperature of the isotherm at 1800, 2400, and 0600 hours has been truncated. However, the plume is not felt downwind, and the upwind and downwind surface temperatures are nearly identical. A surface temperature inversion develops at night and is seen to be deeper over the rural area than over the city. This is indicative of the nocturnal heat island, which decreases the stability of the atmosphere. The magnitude of this heat island is larger at night than during the day. This type of behavior is well documented *(Peterson 1969, Oke 1973b)*. Just after sunrise (0600) the breakup of the stable layer was noted. The surface inversion breaks up rapidly after sunrise due to heating of the surface by absorption of solar radiation, and by 0900 all traces of the inversion have disappeared. Similar types of diurnal variation of thermal structure have been found for other simulations under different conditions *(Johnson 1975)*.

The maximum temperature difference between simulations with radiatively participating and nonparticipatng pollutants occurs at the urban center late at night (fig. 8). The temperature differences are seen to be largest near the surface and are confined to the lowest 600 meters of the PBL. When the pollutant gas is assumed to have the radiative properties of sulfur dioxide (SO_2), the temperature structure predicted is practically the same as that for the

Figure 7.—Isopleths of potential temperature (in K); Gaussian distribution, radiatively nonparticipating, u_g=6 m/s, v_g=4 m/s.

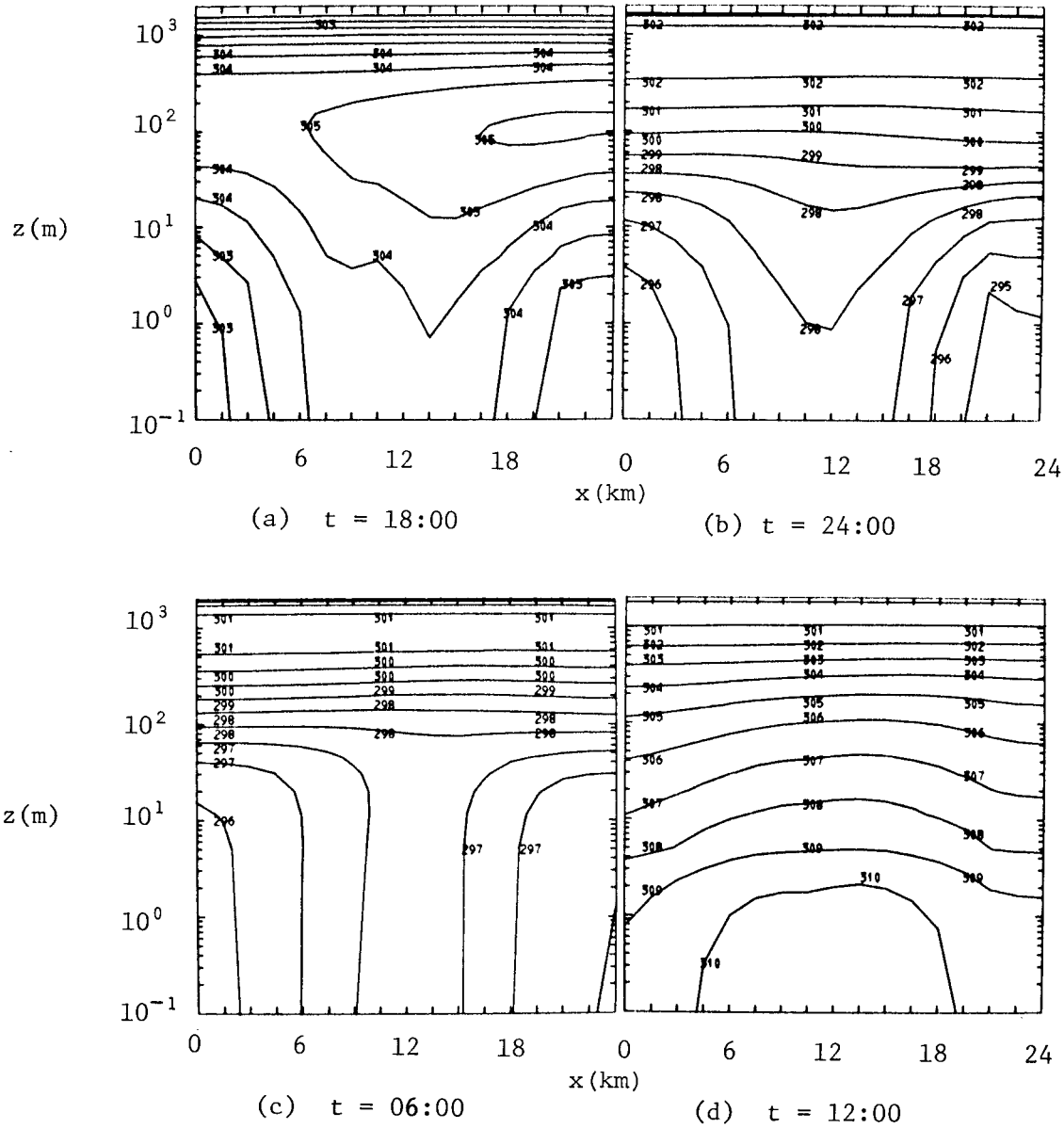
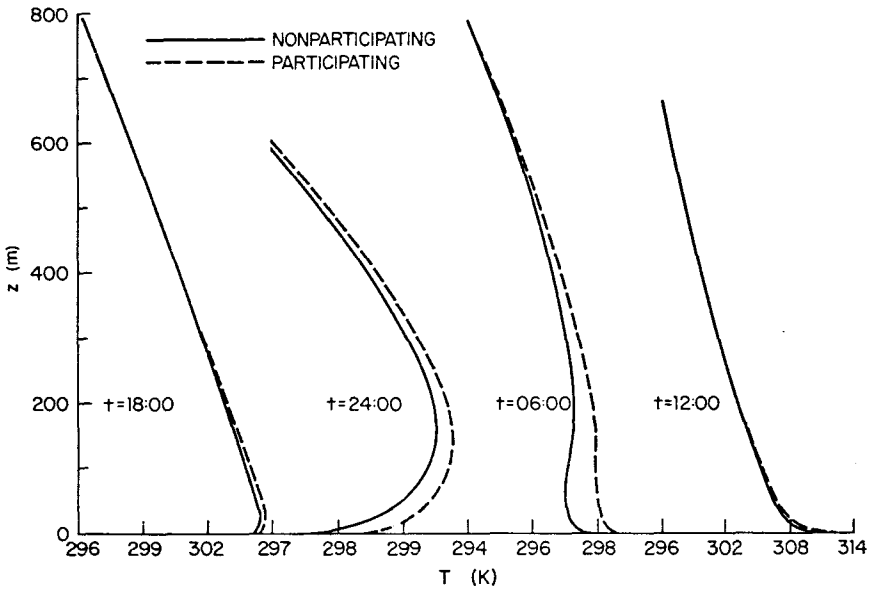


Figure 8.—Comparison of thermodynamic temperatures at the urban center; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, $m_1=m_2=2.5$ $\mu g/m^2s$.



radiatively nonparticipating pollutant gas. This is due to the fact that SO_2 is a weakly radiating gas. The results are consistent with those obtained with the one-dimensional model *(Bergstrom and Viskanta 1973a)*. The net effect of the city and the human activity on the temperature distribution is illustrated in figure 9. The results show that the presence of radatively participating pollutants dampens the amplitude of the diurnal temperature variations and that for a relatively short (24-hour) simulation the effects are confined primarily below 600 m.

Urban Heat Island

The urban heat island is a well-known and accepted fact *(Peterson 1969, Oke 1973b)*. The urban heat-island itensity (maximum difference between upwind rural and highest urban surface temperature, Δt_{u-r}) predicted is shown in figure 10. For the assumed Gaussian distribution of man-made heat sources, the maximum surface temperature difference occurred at the urban center, whereas for the rectangular distribution during the night it occurred downwind of the center. The results presented in the figure show that there is a double peak in ΔT_{u-r}. The first peak is noted at about 2000. It arises due to the more rapid cooling at the upwind rural area than in the city. The maximum heat-island intensity occurs just before sunrise and has a magnitude of about 4°C. For the population of the urban area and wind speeds of the simulation this value is in good agreement with the observations and empirical correlation of Oke *(1973b)*. For a simulation with lower wind speeds ($u_g \simeq 2.4$ m/s and $v_g \simeq 1.6$ m/s), which are not reported here, the maximum heat-island intensity reached about 10°C. This is also in good agreement with the nighttime and daytime observed temperature excesses between the urban and rural locations *(Oke 1973b, DeMarrais 1975)*.

CONCLUSIONS

As a result of a limited number of numerical simulations that have been

Figure 9.—Comparison of perturbation potential temperatures (temperature in the city minus the temperature at the upwind rural location) at the urban center for radiatively nonparticipating (a) and radiatively participating (b) simulations; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, $m_1=m_2=2.5$ μg/m^{2}s.

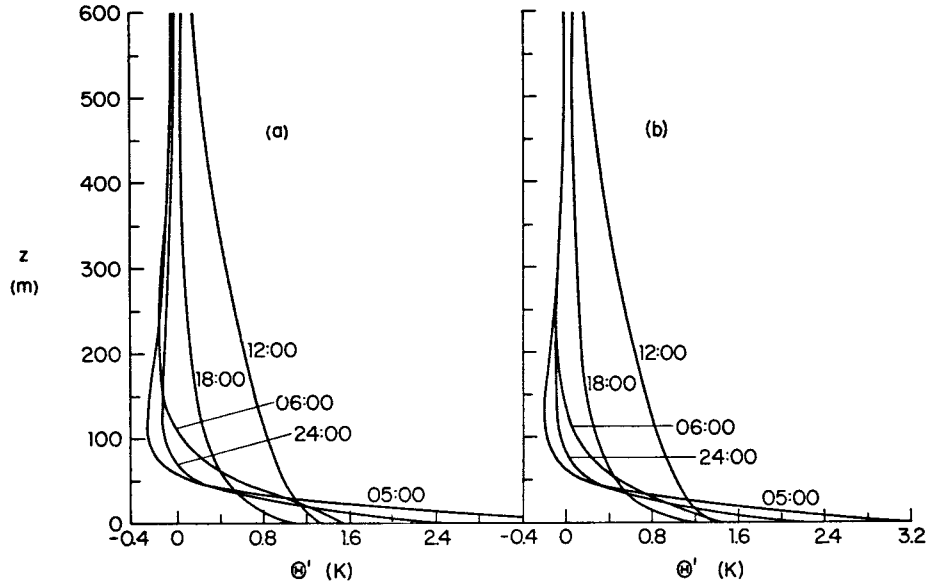
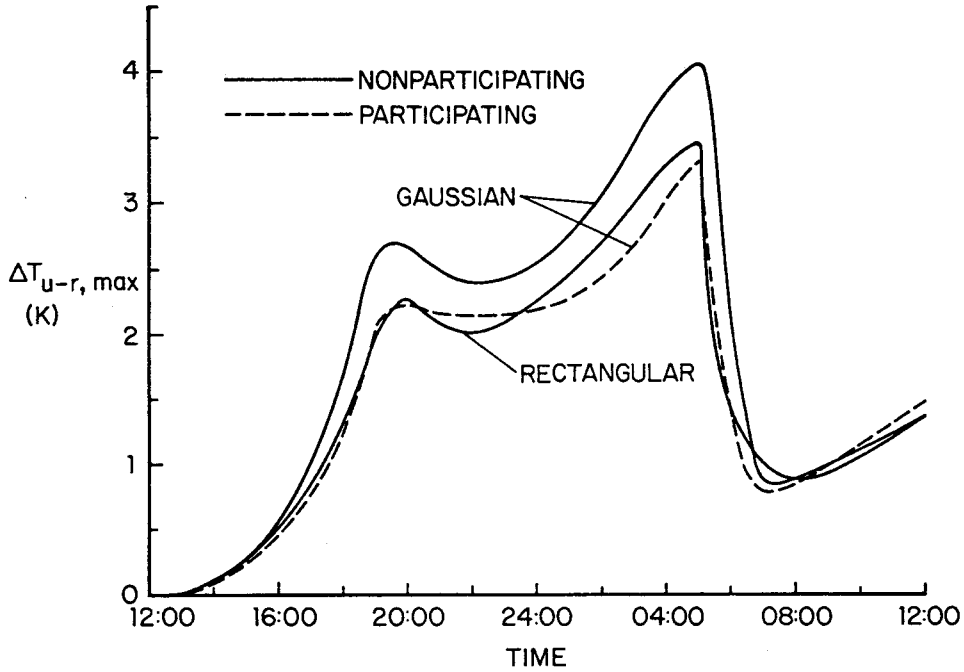


Figure 10.—Comparison of maximum urban upwind rural surface temperature differences; ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, $m_1=m_2=2.5$ μg/m^{2}s.



performed for selected meteorological conditions during the summer, the following generalizations can be made:

1. The unsteady two-dimensional transport model predicts an urban heat-island intensity that is sensitive to wind speed and latent energy transport through Halstead's moisture parameter. The intensity of the urban heat island reached a magnitude of about 4°C near sunrise and about 1.4°C at noon.
2. For the conditions studied, the radiatively participating pollutants are relatively unimportant in forming the urban heat island compared to other factors. During the night, air pollution does increase the surface temperature by about 1.25°C at the urban center.
3. The role of radiatively participating pollutants in the formation of the thermal structure is relatively small and it is greatest late at night. The largest effect of pollutants was to decrease the stability at night and hence increase turbulent transport near the surface particularly at heights below 500 m.
4. The feedback mechanism between pollution, thermal structure, stability, and dispersion has the potential of being significant in modifying pollutant concentrations under more stable conditions and higher pollutant loadings. However, the magnitudes of the changes are dependent on the coupling between the radiative properties of air pollution and the buoyancy-enhanced turbulence. Due to the uncertainties involved in predicting either of these two quantities, the magnitude of these changes is uncertain.

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Acknowledgments. This work was supported by the Division of Meteorology, U.S. Environmental Protection Agency, under Grant No. R801102 and R803514. Computer facilities were made available by Purdue University and the National Center for Atmospheric Research. The interest and support of J. T. Peterson, grant project officer, is acknowledged with sincere thanks. The authors also thank A. Venkatram for his contributions to this effort.

A Preliminary Investigation of the Nocturnal Temperature Structure above the City of Edmonton, Alberta

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ABSTRACT.—Information about the nocturnal temperature structure over Edmonton, Alberta. Observations of the temperature fields, including two- and three-dimensional forms of the nocturnal heat island, were obtained from minisonde ascents, an instrumented helicopter, and towers during a 3-week urban air-pollution field study. Results show that urban-induced temperature modification is typically in the lowest 100 m above ground. Along the direction of the prevailing wind, there is a progressive modification of very stable upwind air as it flows toward the city center, the urban air being less stable. Implications of these observed features on urban air pollutants are discussed.

THE NOCTURNAL TEMPERATURE in the lowest few hundred meters above urban areas has received much attention in recent years *(Oke 1974, Garstang et al. 1975)*. Observations have shown that the city's influence on the nocturnal temperature regime commonly can extend up to 300 m and that thermal boundary layers are generated as stable upwind rural air is advected over a warm urban surface. This sometimes results in a well-defined urban thermal and pollution plume extending aloft and downwind of the city. Within the modified urban air, temperature profiles often exhibit near-neutral conditions, thereby supporting the contention of a well-mixed urban layer. Accordingly, there is usually a marked decrease in frequency and intensity of ground-based inversions over urban areas compared to those over adjacent rural surroundings.

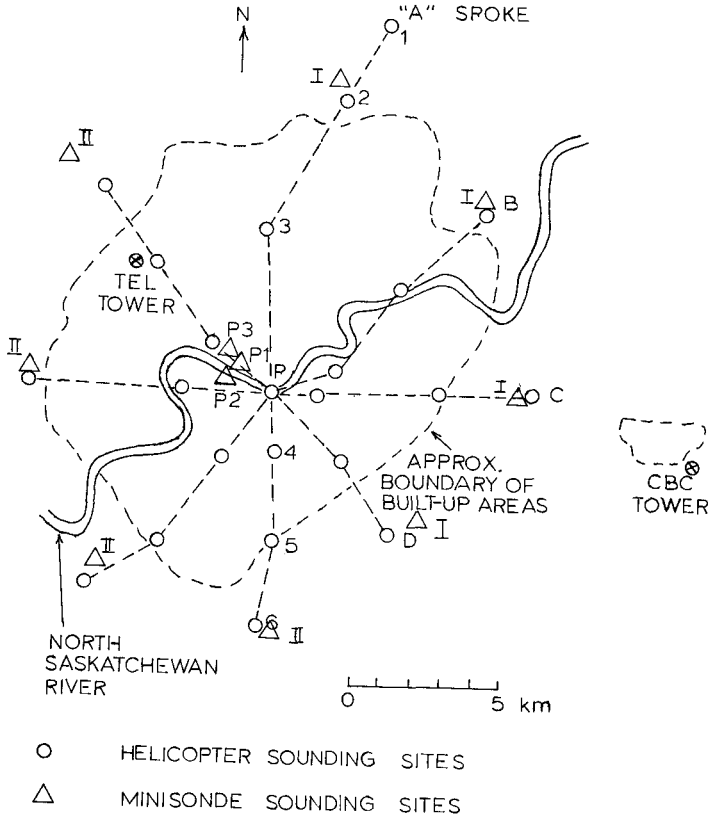
The development of this modified layer above the city is generally attributed to any one or a combination of the following processes: (1) thermal turbulence due to anthropogenic sources or to the release of stored heat in urban structures, (2) mechanical turbulence generated by air flow over urban roughness elements and subsequent redistribution of heat, and (3) radiative processes in the urban atmosphere.

The purpose of this paper is to present some qualitive and quantitative aspects (including spatial characteristics) of the nocturnal temperature regime and associated boundary layer structure over Edmonton, Alberta. The implications for urban air-pollution modelling are also discussed. The study is based primarily on low-level temperature-profile measurements obtained in and near Edmonton during an intensive 3-week urban-air-pollution field study in November and December 1974.

EXPERIMENTAL SITE AND PROCEDURE

Edmonton, a medium-size city with a population of about 0.5 million, was selected as the target for this urban meteorological and pollution study. The city is located on the banks of the North Saskatchewan River in Central Alberta (53°33'N,113°30'W). The topography is generally flat except near the river valley, which runs in an approximately northeast-southwest line through the city (fig. 1). There the valley is steep-sided and narrow, with an average

Figure 1.—Map of the Edmonton area and sampling scheme for probing the urban atmosphere.



depth of about 50 m. From the river banks, the land rises gradually, the most significant change being to the southeast (a slope of 1:200 at 15 km from the city center). The extent of the built-up area is shown in figure 1. The urban core consists primarily of medium-density structures. This is surrounded by mixed low-density commercial and residential areas. Heavy industries are mostly on the eastern fringes of the built-up areas.

The synoptic-meteorological conditions during the investigation period (19 November to 5 December 1974) were near normal for this time of the year, with one notable exception: a lack of significant snow cover in the region. Otherwise typical winter characteristics prevailed. This period was chosen in part to maximize the chances of observing well-developed heat-island effects and high air-pollution episodes.

For the monitoring of low-level temperature profiles, two mobile minisonde systems, a helicopter, and two instrumented towers were used. The minisonde system is a lightweight version of the radiosonde. It consists of a small inexpensive fast-response temperature sonde (microbead thermistor, time constant 1.5 s, relative accuracy 0.2° C), which is carried aloft by a standard pilot balloon with a rise rate of about 3 m/s. Heights and winds aloft were

obtained by tracking the balloon via the double-theodolite method. The helicopter was equipped with a Sign-X temperature unit, along with pollution-measuring equipment. The temperature sensor for this unit consisted of a shielded thermistor with a response time of about 0.5 s and a relative accuracy of 0.2°C. Heights were obtained from a pressure transducer with a similar response time and a relative accuracy of 5 m.

Supplementary temperature information was obtained from two instrumented towers (fig. 1) operated by the Atmospheric Environment Service, Canada. Both the telephone and CBC towers (urban and rural respectively) are equipped with Rosemount platinum resistance thermometers in aspirated radiation shields and with linear matching bridges at heights of 10.0 and 91.5 m above ground. An additional temperature sensor is located at the 45.7-m level on the urban tower. Wind measurements on both towers were recorded at the 91.5-m level.

The adopted sampling scheme for probing the urban atmosphere is also shown in figure 1. Nocturnal measurements, utilizing the minisonde system, consisted of comparative urban and upwind rural temperature profiles during the periods shortly after sunset and before sunrise. Eleven simultaneous comparisons were obtained. One minisonde unit was used at a fixed location near the city center (P1, P2, or P3) depending on the prevailing wind. Simultaneously, the second unit monitored the nearby upwind rural profile at locations A, B, C, or D (I or II), also depending on the prevailing wind.

On two occasions, 12 minisonde ascents were made along two transects across the city, one line perpendicular to the other, to investigate the spatial structure of the boundary layer. At selected points along the spokes A, B, C, or D, helicopter soundings near sunrise provided vertical profiles of temperature upwind, over, and downwind of the urban area. In addition, the instrumented towers gave continuous nocturnal measurements of low-level urban and rural temperature gradients during the entire study period.

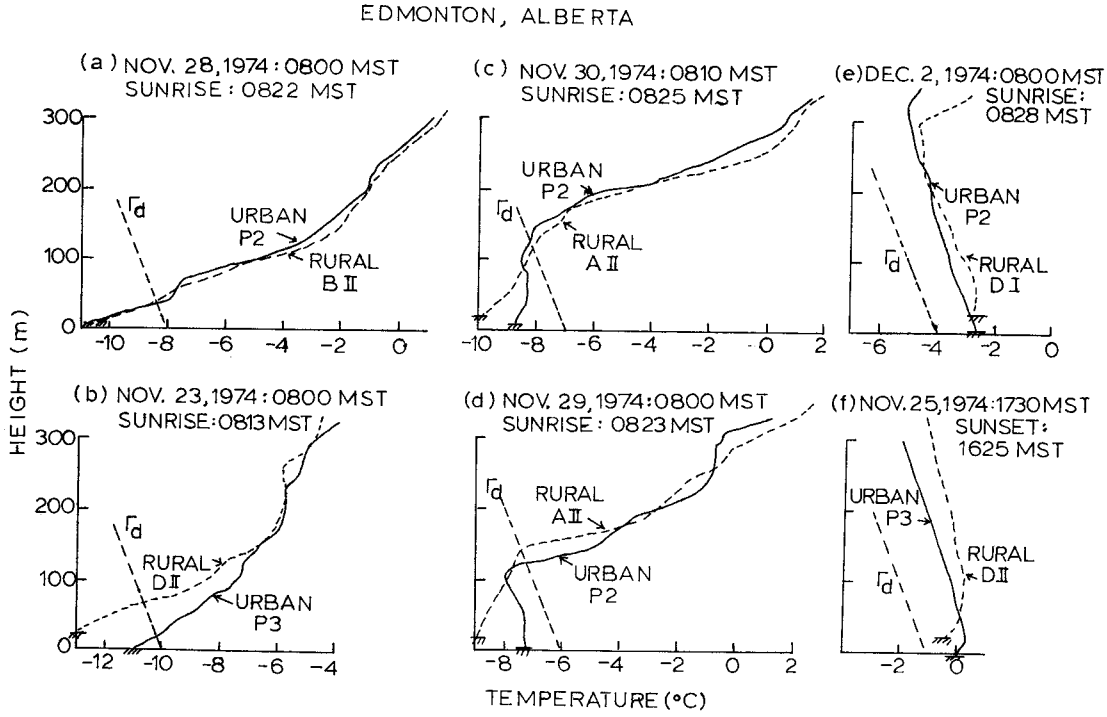
URBAN AND UPWIND RURAL TEMPERATURE PROFILES

Typical examples of comparative urban and upwind rural nocturnal temperature profiles, based on minisonde ascents, are shown in figure 2. These were selected primarily to illustrate the wide range in urban atmospheric temperature profiles than can occur under inversion conditions in the nearby upwind rural areas.

In figure 2(a), the prevailing wind was from the southwest with speeds below 4.0 m/s in the lowest 100 m. Despite the lack of significant snow cover in the area, intense and deep surface-based inversions (6.9°C/100 m in the low-levels, inversion top at 430 m) occurred at both urban and rural sounding sites. As no urban-induced temperature effects are discernable, it is not possible to define a mixed or modified layer. This suggests that radiative cooling over the southwestern areas of the city was at least as intense as that over the nearby rural surroundings. In this sector of the city, larger segments of green areas than urbanized land occur. It was noted, however, that similar urban and rural inversion profiles occurred on occasions with westerly winds.

The situation, illustrated in figure 2(b), is for a northwest wind. Typical wind speeds were less than 2.5 m/s below 100 m, and less than 5.0 m/s in the layer between 100 and 200 m. The upwind rural inversion was both intense and deep. The air trajectory was mainly over built-up areas as it approached the urban site. A significant heat island, decreasing with height, was evident. Noteworthy, however, was the fact that the modified urban layer, about 140 m deep, remained strongly stable (3.2°C/100 m inversion), although slightly weakened

Figure 2.—Examples of simultaneous urban and upwind rural temperature profiles from the minisonde systems for the period between sunset and sunrise.



in comparison to that in the rural environment. This type of effect was observed on several nights. The dominance of radiative processes over the relatively low-density urban structures would perhaps explain this type of urban profile.

Another situation that occurred commonly is shown in figure 2(c). Here, the upwind rural site was characterized by a ground-based inversion, more intense aloft than near the ground. Winds were from the south, and speeds were less than 0.5 m/s below 20 m, increasing to about 4.5 m/s in the layer 20 to 100 m. At the urban site, the profile is near isothermal below 100 m. This type of modification may also be ascribed to radiation processes as suggested by Hage and Longley *(1970)*, in which the city experiences less radiative heat loss than the surrounding countryside. Radiation equilibrium (isothermal) conditions would thus be expected with increasing urban heat-island intensities.

As in the previous example, figure 2(d) shows similar upwind rural conditions with a southerly flow. Wind speeds, however, were much stronger, 4 to 5 m/s below 50 m, and about 10.0 m/s between 50 and 100 m. A well-defined mixing layer (about 100 m deep) with near adiabatic conditions, developed over the urban site. This type of urban profile has been observed often in mid-latitude cities *(Clarke and McElroy 1974)* and supports Summers *(1967)* concept of the city acting as a heat source to create its own mixed layer characterized by an adiabatic lapse rate. In this particular example, mechanical turbulence, thermal turbulence, and radiative factors probably all contributed to the modification process.

Figure 2(e), a situation for southeast winds, indicates considerable modification below 300 m at both urban and rural sites. Wind speeds ranged from 3 to 6 m/s in the lowest 50 m. Between

50 and 100 m, speeds increased to about 10 m/s and for the subsequent 200 m aloft, averaged about 13 m/s. Lapse rates below the inversion were near adiabatic. As the modification occurred both inside and outside the city, the dominant influence is considered to be of meso-scale extent. The presence of extensive cloud cover on this morning would appear to support this. The slight increase in mixing depth over the city may have been caused by additional mechanical turbulence over urban roughness elements.

Last, figure 2(f) illustrates an example of conditions after sunset for a northwest wind. Shallow ground-based inversions at both urban and rural sites were evident, despite the fact that wind speeds averaged about 7.0 m/s in the lowest 50 m depth. There was, in addition, a small heat-island effect. The urban inversion was slightly weaker in intensity than that over the rural site.

These examples offer some insight into the problems of defining or predicting the nocturnal urban boundary layer. In the past, this layer, expressed in the form of an urban mixing layer, has often incorporated in air-quality dispersion models. The recent works of Clarke and McElroy *(1974)* and DeMarrais *(1975)* suggest that the depth of the nocturnal boundary layer over the center of the city can be estimated from the temperature structure of the upwind rural environs or by the dry adiabatic extension of the maximum heat-island temperature to an upwind rural temperature profile.

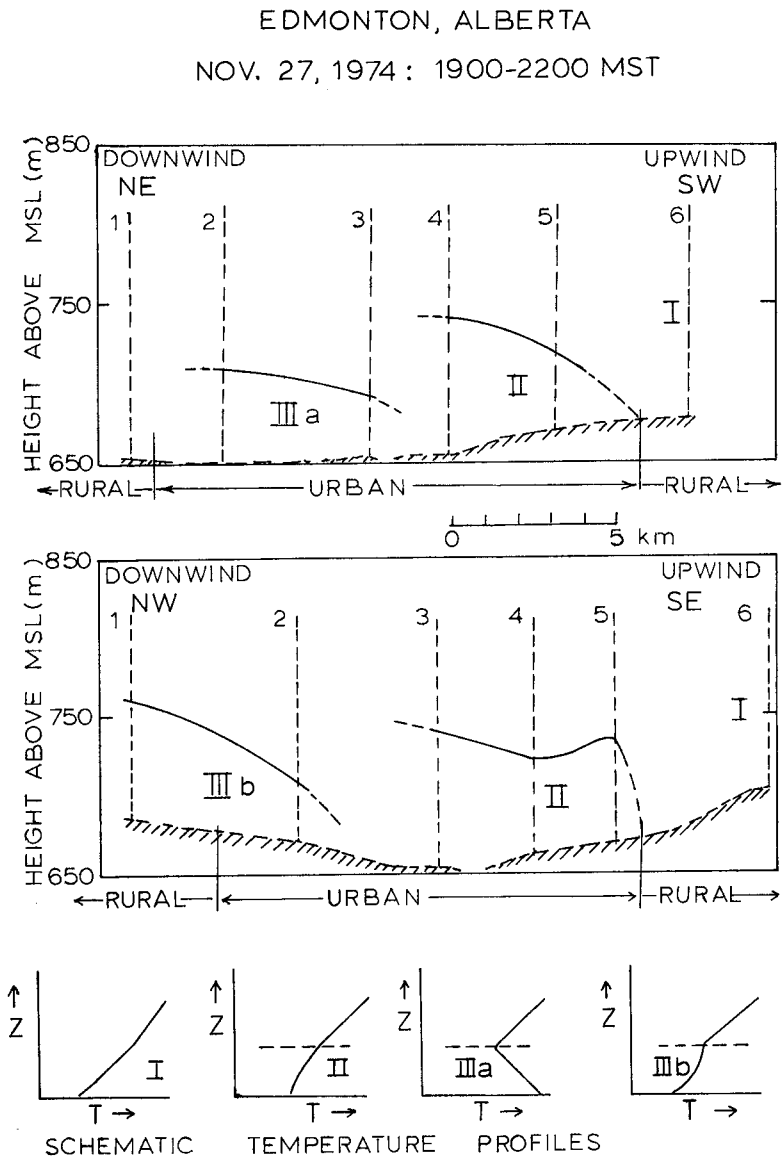
Such techniques unfortunately do not seem suitable for the situation observed in Edmonton, where a near-adiabatic assumption may often be inapplicable. Indeed, the concept of a nocturnal urban mixing depth, with the important implication of a more or less uniform vertical distribution of pollution, would perhaps be more aptly replaced by the term 'modified depth', in which the urban lapse rate can range from inversion to adiabatic and in which pollution can be stratified. Land-use patterns and associated radiative processes, as well as mechanical and thermal turbulence effects, could then be combined with information on the upwind rural temperature profile to formulate a scheme to predict this modified depth (including its nonoccurrence). The use of a modified depth to define the nocturnal urban boundary layer thickness over Edmonton yields values typically of about 100 m or less near the city center. This corresponds to a boundary layer slope of 1:50 or shallower.

NOCTURNAL URBAN BOUNDARY LAYER STRUCTURE

Spatial aspects of the boundary layer structure over Edmonton were investigated on two nights, 27 November (1900-2200 MST) and 30 November (0500-0810 MST). On both occasions, minisonde ascents were made along two transects, perpendicular to each other, across the city. These low-level profiles were then used to estimate the thickness of the modified depth and the shape and structure of the urban boundary layer. The height of the modified depth was identified as that point on the temperature profile (a continuous temperature trace output) above which the gradient approximately coincided with that of the upwind rural profile or, in some instances, the point where a distinct change in gradient on the urban profile could be readily identified.

Figure 3 shows the boundary layer structure for 27 November along with schematics of the observed temperature profiles. Southerly winds prevailed during this experiment, with mean speeds of about 2.5 m/s below 50 m and 5.5 m/s between 50 and 100 m. The two transects, northeast-to-southwest and northwest-to-southeast, closely followed spokes B and D, respectively (fig. 1). The upwind rural area was denoted region I. Here similar ground-based inversions occurred, both southeast and southwest

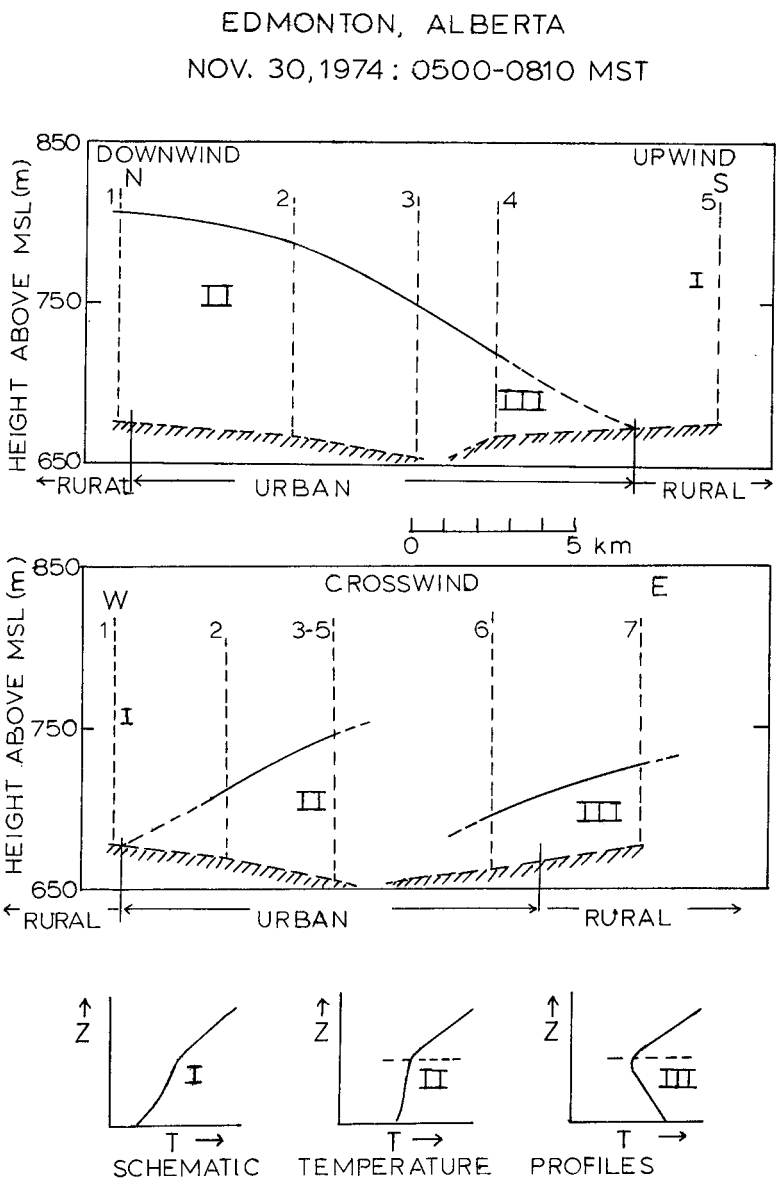
Figure 3.—The nocturnal boundary layer structure over Edmonton on the late evening of 27 November 1974.



of the city center. The characteristic temperature profile of this region was assumed to extend to the edge of the upwind built-up areas. As the air flowed across urbanized land, region II developed, consisting of a modified layer of less intense inversions and a general progressive increase in boundary layer thickness towards the urban center. Further downwind, a second boundary layer could be identified (designated regions, IIIa and IIIb). Here, lapse rate in the modified layer was extremely unstable (superadiabatic) to the northeast, whereas it was relatively stable and of distinct shape to the northwest. Boundary-layer depth on this night over the city was confined to the lowest 100 m.

The second experiment (fig. 4) showed

Figure 4.—Along-wind and cross-wind structures of the nocturnal boundary layer over Edmonton on the early morning of 30 November 1974.



the structure on the early morning of 30 November. The two transects, north-south and east-west, closely followed spokes A and C respectively (fig. 1). The air flow was again from the south. Wind speeds below 20 m were light, about 1.0 m/s, increasing to about 4.5 m/s in the layer 20 to 100 m. Along the direction of the wind, an increasing boundary layer could be identified from the upwind south side across to the downwind side of the city. In this layer of modified air, temperature profiles decreased in stability from near adiabatic upwind to slightly stable downwind of the city center. Crosswind, the boundary layer structure closely resembled that which was observed on 27

November (fig. 3). These examples of the spatial nature of the nocturnal urban boundary layer over Edmonton are believed to reflect the heteorogenous nature of the urban surfaces.

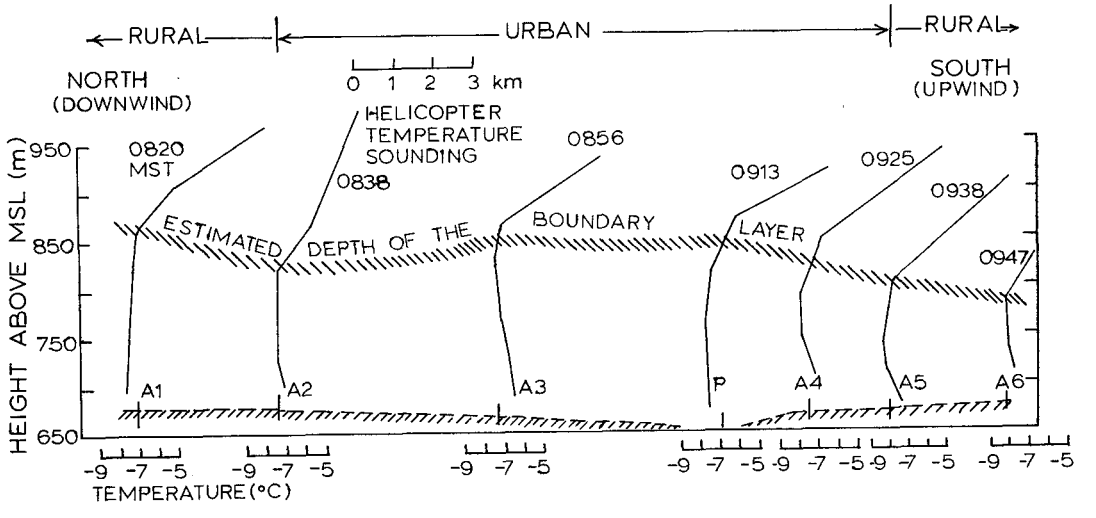
URBAN BOUNDARY LAYER STRUCTURE NEAR SUNRISE

Observations of the boundary-layer structure over Edmonton from detailed helicopter temperature profiles were made only during daylight hours because of restriction on night-time flying. Hence, for this study, only the measurements near sunrise were considered relevant. These provided information on the temporal evolution of the nocturnal boundary layer through the sunrise transition period.

The example (fig. 5) was obtained on the morning of 30 November (0800-1000 MST) along spoke A (fig. 1). It depicts the temperature structure upwind of, over, and downwind of the urban area, along with the associated boundary layer, and, in addition, it represents the evolution of the nocturnal boundary layer (fig. 4) through the sunrise transition period. Wind direction and speeds remained almost the same as previously given for the period 0500-0810 MST.

The most significant change in boundary-layer shape and depth occurred over the upwind rural areas. Here the nocturnal ground-based inversions were destroyed up to a depth of about 120 m through natural convection processes within an hour and a half after sunrise. This effect was observed on most late-morning temperature soundings from both the minisonde and helicopter measurements. In general, the effect of solar radiation and subsequent warming from below created significant daytime rural mixing depths of almost similar magnitude to that over the urban areas by mid-day. The structure below the boundary layer closely followed that observed before sunrise (fig. 5). Profiles generally decreased in stability along the direction of the prevailing wind, from near adiabatic upwind to slightly stable on the downwind side of the city.

Figure 5.—Helicopter temperature profiles across Edmonton in the direction of the prevailing wind at and after sunrise on 30 November 1974. The inferred shape and depth of the boundary layer are also indicated.



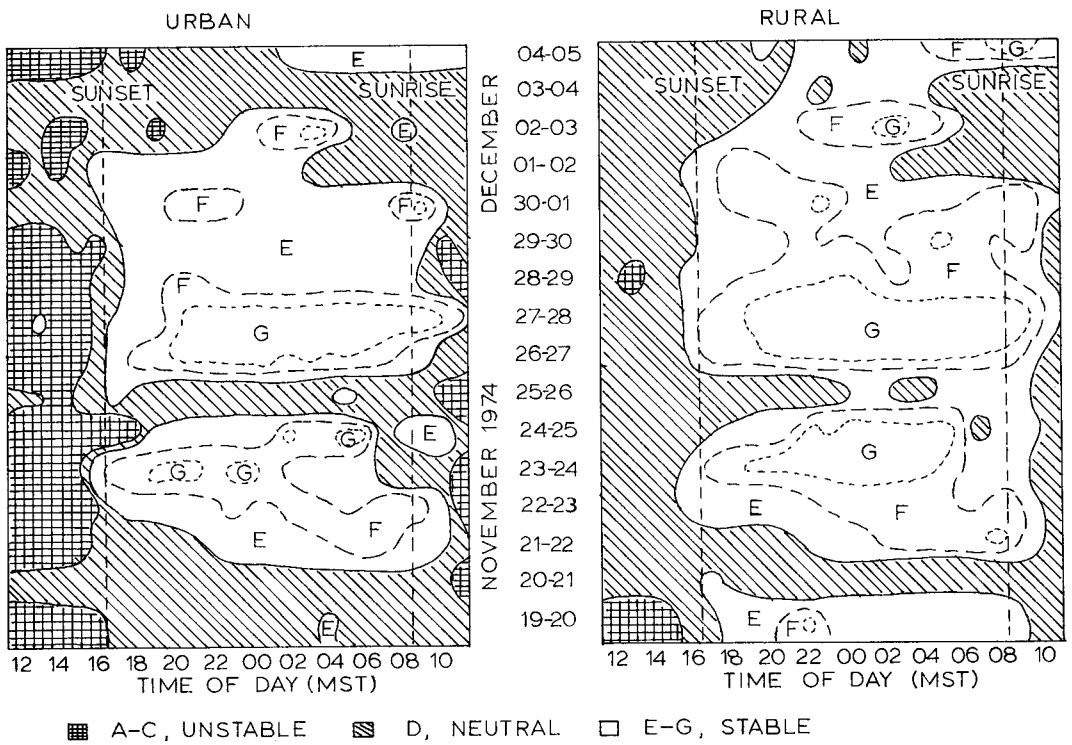
URBAN AND RURAL TOWER STABILITIES

The hourly vertical temperature gradients, monitored between 10.0 and 91.5 m on the urban and rural towers during the period 19 November to 5 December 1974, were used to approximate low-level stabilities in and near Edmonton. Initially, the gradients were examined in terms of Pasquill stability categories as defined by USAEC (1972) (table 1). The stability patterns are illustrated in figure 6. Between sunset and sunrise, both urban and rural towers showed a prevalence of stable conditions (63 and 78 percent respectively). An examination of these nocturnal stability patterns indicates that, relative to the rural environs, the urban site is characterized by no change in stability 56 percent of the time, decreased stability 42 percent, and increased stability 2 percent. Of the cases with decreased stabilities, a change by one stability category (D to C, E to

Table 1.—Classification of atmospheric stability

Stability classification	Pasquill categories	Temperature change with height (°C/100 m)
Extremely unstable	A	< —1.9
Moderately unstable	B	—1.9 to —1.7
Slightly unstable	C	—1.7 to —1.5
Neutral	D	—1.5 to —0.5
Slightly stable	E	—0.5 to 1.5
Moderately stable	F	1.5 to 4.0
Extremely stable	G	> 4.0

Figure 6.—Urban and rural tower stabilities (temperature gradients) in Edmonton during the period 19 November to 5 December 1974.



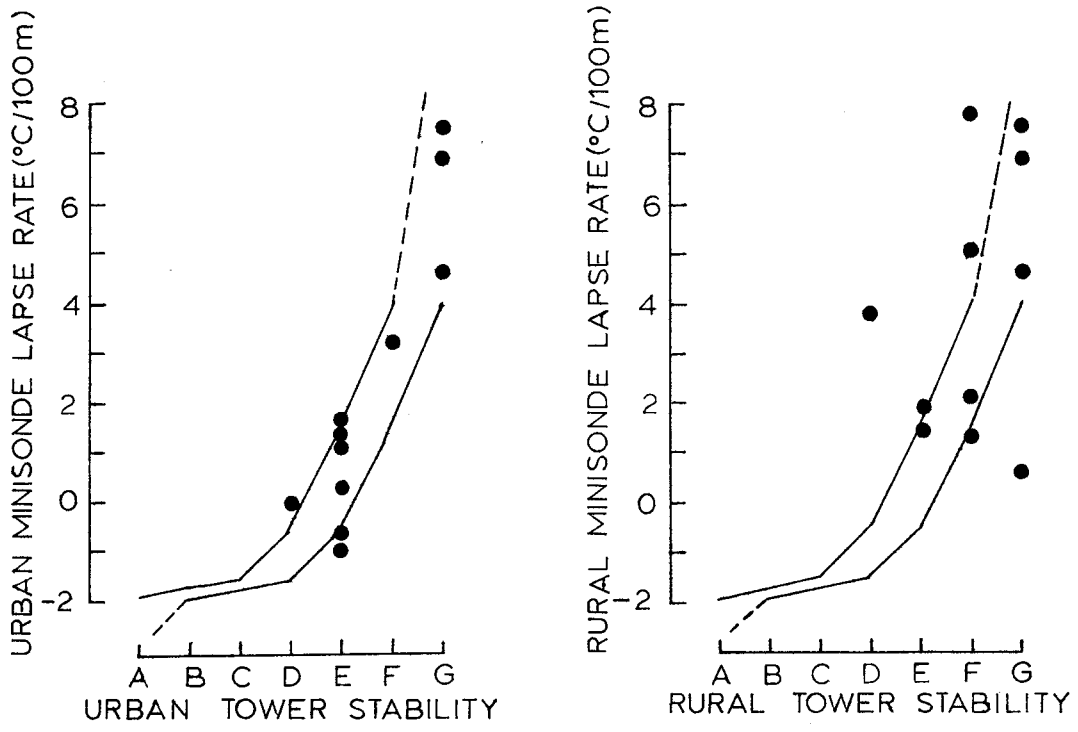
D, etc.) occurred on 83 percent of the occasions. If the cases of coinciding neutral stability (D) on both towers are excluded (such conditions being likely to occur under overcast conditions, regardless of urban or rural terrain), the following urban stability changes are obtained: no change 45 percent, decreased stability 53 percent, and increased stability 2 percent.

A comparative study of the nocturnal stability variations between 10.0 and 45.7 m with that between 10.0 and 91.5 m on the urban tower gave no difference in stability 69 percent of the time. For the other occasions, stability variations with height were almost equally shared between an increase and a decrease. Hence, it was inferred that vertical stability changes on the urban tower were relatively insignificant.

The tower data suggested that two dominant patterns are likely to occur in the lower urban atmosphere with stable nocturnal rural conditions: in one case, no change between urban and rural stabilities; in the other, a decrease of one stability category over the urban area. The latter situation is commonly assumed for estimating the vertical diffusion length over a city *(Gifford 1972)*. These nocturnal features are in general agreement with the detailed observations of temperature profiles previously discussed. In addition, the persistence of inversion conditions on the urban tower for a few hours after sunrise on several mornings (fig. 6) agrees with the minisonde results, which showed urban ground-based inversions around 0930 MST on 22, 23, and 28 November 1974.

A comparison of the 11 simultaneous upwind rural and urban minisonde soundings at night with the rural and urban tower stabilities for the same time periods is given in figure 7. From the urban profiles, lapse rates within the

Figure 7.—Comparison of the low-level lapse rates from minisonde ascents with the tower stabilities at night.



modified layers, or in some instances, the lowest 100 to 150 m above ground (cases of no modification) were estimated. The lowest 100 to 150 m were used to obtain the rural lapse rates also. In figure 7 the solid-dashed lines represent the envelope relationship between temperature gradients and stability *(USAEC 1972)*. In general, the urban tower stabilities showed good agreement with the minisonde derived urban lapse rates. There was slightly less agreement between the rural tower stabilities and the rural minisonde lapse rates. This was not surprising because the rural tower stabilities may not always be representative of conditions upwind of the city. This limited comparison suggested that the urban tower stabilities may yield reasonable approximations of diffusion characteristics within the modified urban layer over Edmonton and may be potentially useful in the development of an urban dispersion climatology of the area.

CONCLUSION

This preliminary investigation of the nocturnal temperature structure over Edmonton provided some experimental evidence of the manner in which a medium-size city can alter the lower atmospheric thermal regime and the associated boundary layer structure. In contrast to similar investigations for other mid-latitude cities, the results here showed a wide range in urban-induced temperature modification (from inversion to adiabatic and in some instances, no change) when stable upwind rural air is advected over the city.

On the average, nocturnal boundary layer depth seldom exceeded 100 m. Within this modified layer, lapse rates were often stable (inversion). Hence, it is suggested that the term "urban nocturnal mixing depth" would be more aptly replaced by the term "urban nocturnal modified layer" and that suitable techniques should be developed to predict this depth in which the lapse rate can vary over a wide range.

Case studies of the variation in the nocturnal boundary layer structure exhibited complex patterns that seem to reflect the heteorogeneous nature of the urban surface. Urban tower gradients, expressed in terms of Pasquill Stability categories, indicated two dominant regimes: no change in stability, and a decrease by one stability category (less stable) as compared to simultaneous rural values. The determination of these urban stabilities from tower measurements could be applied usefully in developing an urban dispersion climatology for the area.

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Acknowledgments. Special thanks are due to the many participants in the Edmonton Air Pollution Field Study. They included groups from the Atmospheric Environment Service, Canada, the Department of the Environment of the Government of Alberta, the Department of Geography of the University of Alberta, and Western Research and Development Ltd. of Calgary. The experimental part of this study was conducted while the author was affiliated with the Atmospheric Environment Service.

Surface Air Temperature in a Maritime Metropolitan Region

by J. D. McTAGGART-COWAN *and* J. W. S. YOUNG, *respectively with the Atmospheric Environment Service, Environment Canada, Downsview, Ontario; and New Brunswick Department of the Environment, Fredericton, New Brunswick, Canada.*

ABSTRACT.—In investigations of the micrometeorology of any area, one of the basic parameters required is the spatial and temporal distribution of the surface air temperature. A mobile instrument mounted on an automobile was used for measuring temperatures within the surface mixed layer. Details are presented of a case study at Saint John, New Brunswick, in a summer period. The effects of topography, lakes, sea-breezes, and land-use characteristics are discussed.

STATISTICS for climatology of a region that are based on measurements taken at only one point fail to reflect differences in climate within the region. These differences can be especially significant in determining the scope of a tourist industry or in land-use planning on a regional and personal level.

One of the interests many people have is the distribution of surface air temperature within a region. During the summer months, some people like to stay near bodies of water where temperatures are moderated. Others prefer more radical climates where the air is drier but the temperatures vary greatly. Meteorologists are also interested in the surface isotherms, as they give an indication of the state of the atmosphere in the surface mixed layer.

A simple, mobile instrument for measuring these temperatures is described, and an example of the information that can be obtained is given for a maritime metropolitan region.

THE INSTRUMENT

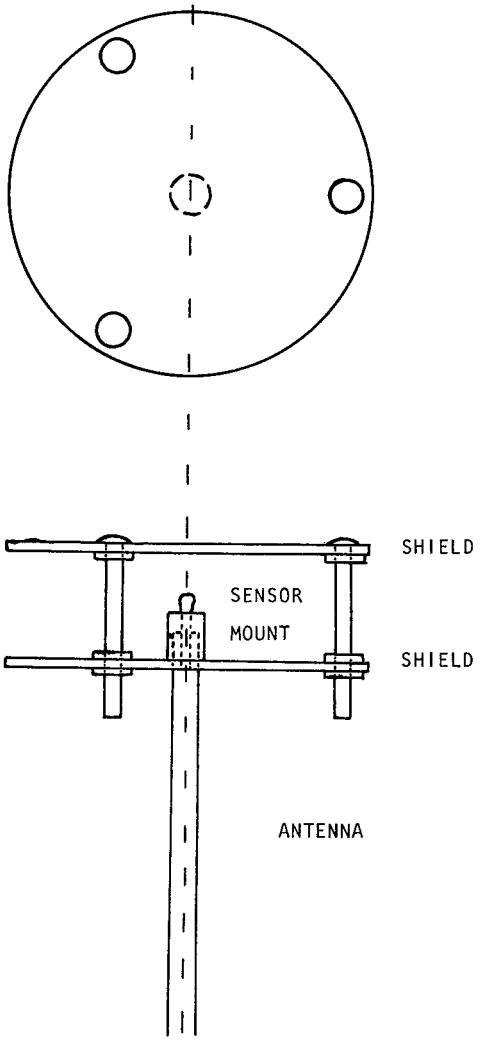
A rugged, dependable, and inexpensive direct-reading temperature system was developed for measuring the air temperature from a moving vehicle. It consists of a sensor and supporting structure (fig. 1), a simple circuit (fig. 2), and a digital voltmeter.

The sensor used is a dual thermistor made by Yellow Springs Instrument Company. These thermistors, when combined in a simple resistive network, produce a device capable of giving reproducible temperatures on a linear scale with a range of about 50°C. (The networks used in this system worked from −5°C to +45°C.)

The thermistor bead (YSI#44018) is mounted securely in a thermally insulating holder that is mounted between two circular plates about 7 cm in diameter. The separation between the plates is such that the bead is screened from the direct rays of the sun (except at low sun angles) and cannot sense the road surface on either side of the transporting vehicle. These plates, held together by three thin vertical struts, are painted shiny white on their outer surfaces and flat black on the inside surfaces. This combination serves as a fairly effective radiation shield for the sensor by blocking off direct and reflected shortwave solar radiation while permitting ample airflow past the sensor.

The bottom plate of the shield and the insulating holder attach to the top of a standard whip antenna, which is mounted on the roof rack of an auto-

Figure 1.—Sensor and supporting structure.

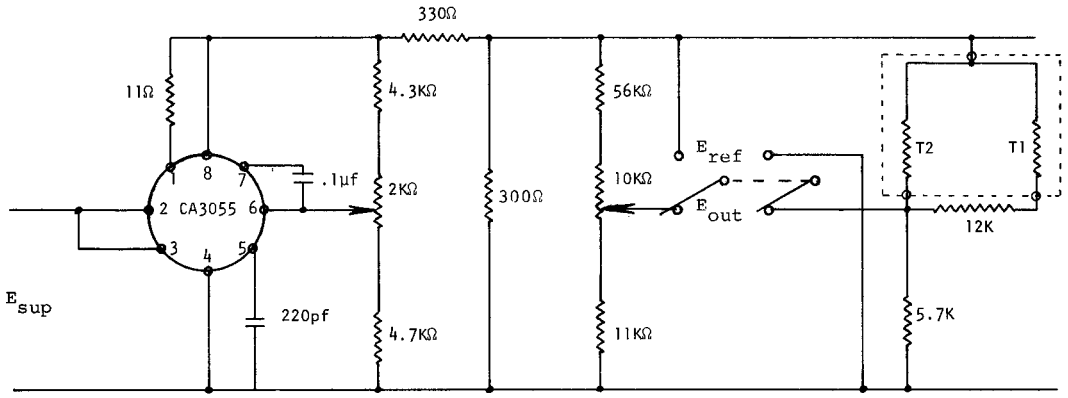


mobile. This allows the sensor to be placed several meters above the ground and at least 1 m above the roof of the transporting vehicle. Several advantages are gained by this type of mounting in that the sensor tends to be above the layer of air directly influenced by the road and thus samples in an area that represents the surroundings. The vehicle motion, which was maintained above 5 m sec^{-1} for all sampling points, produced adequate ventilation for the sensor.

Three wires lead down the mast from the sensor to the signal conditioner box inside the vehicle. This box consists of a constant voltage source generator (such as an RCA3055) working from a 9-V battery, a divider network to drop the output voltage of the regulated supply to a useful level, a zero-offset control, and the resistive network for linearizing the thermistor output. A swith is also included to permit monitoring of the regulated DC voltage, and a variable resistor control allows setting of that voltage when any drift due to system aging is detected.

The output of this box can be monitored by any DC voltmeter. A Weston Digital Voltmeter, Model 1240, was used during the field study reported in this

Figure 2.—The thermistor linearizing circuit. T1 and T2 are the sensor elements; E_{sup} is the battery supply voltage; E_{ref} is the reference voltage chosen using the thermistor's equation to yield a unit change in E_{out} for a 0.1°C change in temperature.



paper. This permitted the temperature to be read directly to 0.1°C. The absolute accuracy of the system is ±0.2°C without calibration, and the system is insensitive to air velocity above 5 m sec^{-1}.

THE FIELD PROGRAM

To investigate the spatial and temporal distribution of surface air temperature in the vicinity of Saint John, New Brunswick, Canada, two identical instruments were constructed, tested, and calibrated.

A grid was laid out on the city map, and a series of stations were identified, based on the criterion that a site selected was to be as close to the center of each grid square as possible but still on a navigable road. This produced 51 separate locations, which were divided into two courses, one on each side of the Saint John River. A continuous loop for each course was chosen, and this became the driving pattern for the two vehicles, each manned by a driver and an observer. Each course took about 1.5 hours of continuous driving to complete, and a minimum of five traverses was run each day.

The temperature at each station was obtained by averaging the readings taken during a 10-second interval centered at the preselected site. These values were then plotted against time to obtain 51 individual daily temperature curves. From these a series of surface isotherm maps was obtained for times corresponding to concurrent vertical profiling of the atmosphere. An example of these maps, showing isotherms drawn every 0.4°C, is given in figure 3. Complete data from this study are given in McTaggart-Cowan *et al. (1974)*.

RESULTS

From these isotherm plots, a number of clearly definable meteorologically influenced events can be observed. The isotherm plot made for 1430 local time on 16 July 1974 (fig. 3) shows the typical detail that can be observed during a sunny afternoon. Temperature differences of 6°C are not uncommon in a distance of 8 km from the edge of the Bay of Fundy. These differences develop rapidly during the summer when the sky is clear.

This particular day also showed the

Figure 3.—Surface isotherms at 1430 on 16 July 1974. The city of Saint John, New Brunswick, straddles the Saint John River just at its mouth. (Map Scale: 1 cm=1780 m).

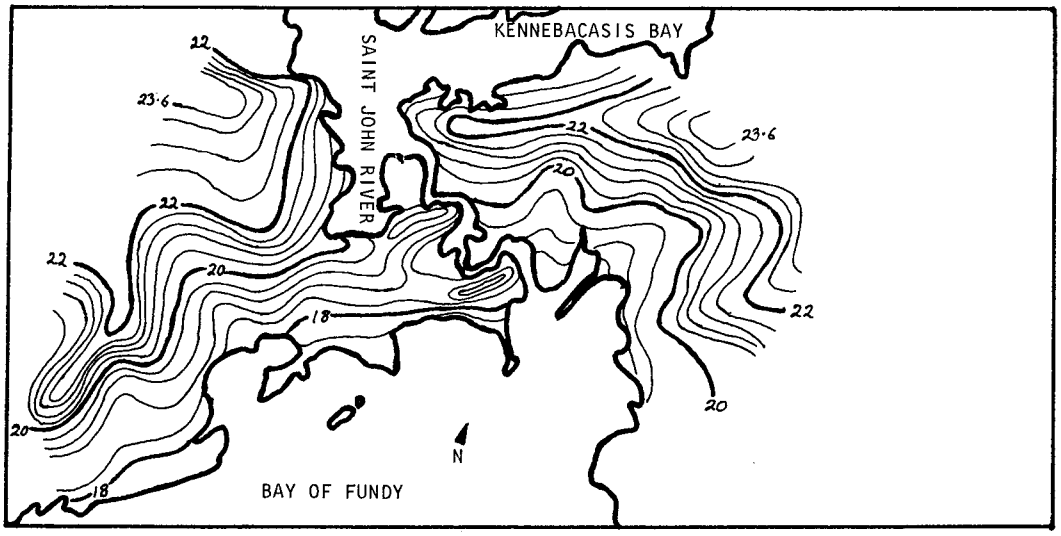
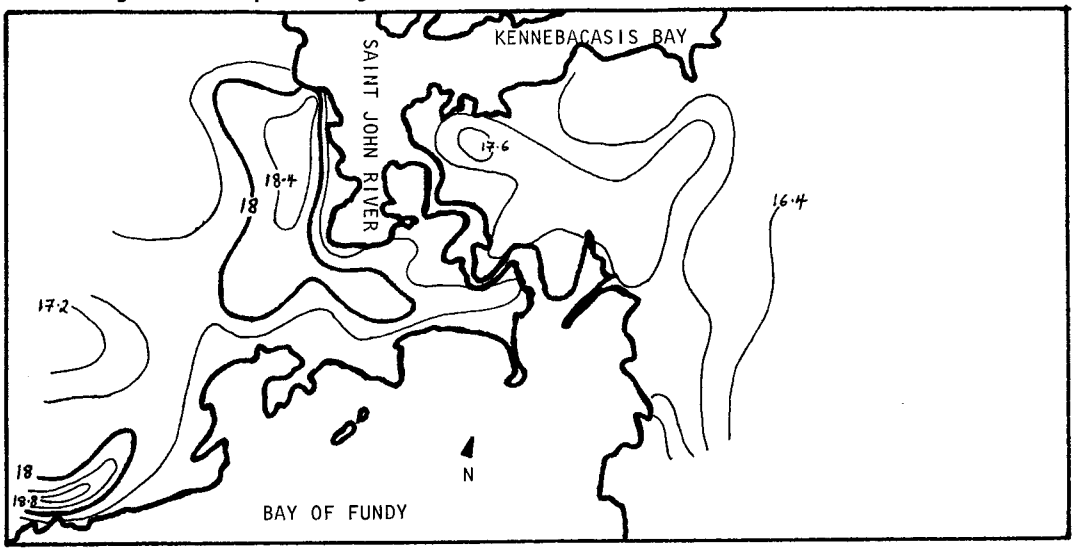


Figure 4.—Surface isotherms at 1000 on 16 July 1974, showing the effect of fog on the temperature gradient.



effect of fog. At 1000, the isotherm map (fig. 4) showed very little structure. The visibility in fog at this time was given as 6 mi, with the sky totally overcast. The sky cleared sometime after 1100, and convective-type clouds were reported by 1500, shortly after the 1430 profile. This type of cloud can be related directly to the strong heating of the surface.

The effect of the sea breeze, a characteristic event of a maritime region, can also be observed in figure 3. The bulge inland of the 20.0° and 22.0° isotherms on the right of the diagram is a result of the colder Bay of Fundy air intruding over the rapidly warming land. In the morning before this developed, the flow was light northerly, but by the afternoon the southwesterly flow of the sea breeze dominated. This resulted in the surface mixed layer temperature near the water being warmer than that further inland in the morning, but cooler later in the day. The moderation of the surface air temperatures in summer near a body of water is clearly shown.

Another example of the effect of a body of water on the surface temperature can be seen in figure 5. In the western portion, the 14.0° isotherm can be seen directly downwind of a lake. The water temperature is higher than the air temperature and, with the westerly flow that was dominant at the time, a tongue of warmer air developed on the lee side of the lake. The splitting of this warmer air flow follows the topography.

Urban versus rural temperature differences can also be demonstrated by isotherm plots. The early morning distribution of temperature on 18 July 1974 (fig. 5) shows the heart of the city with a temperature of 13.2°C, while the countryside is typically below 12°C. This feature is usually masked during clear summer days by the locally generated air flow resulting from the city's proximity to the water.

The plot for 1100 on 18 July 1974 (fig. 6) shows an example of a late-morning situation on a clear sunny day. This plot is similar in complexity to the 1430 plot on 16 July (fig. 3), but has occurred more than 3 hours earlier. Only the full-degree isotherms are shown, as the principal purpose of the figure is to show the effect of topography on the

Figure 5.—Surface isotherms at 0700 on 18 July 1974, showing the effect of Ludgate Lake on the surrounding temperature field and the warming caused by the city center.

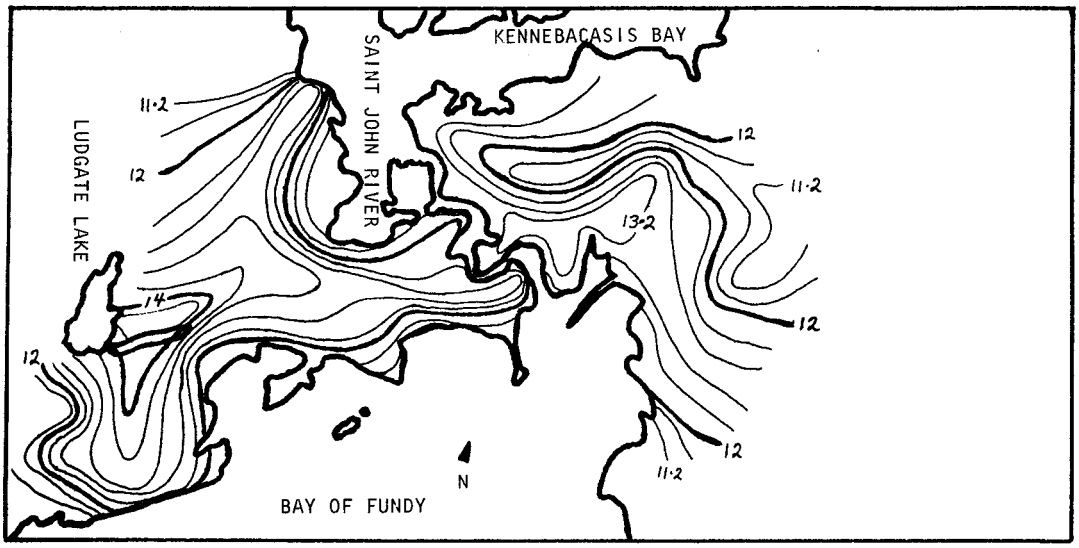
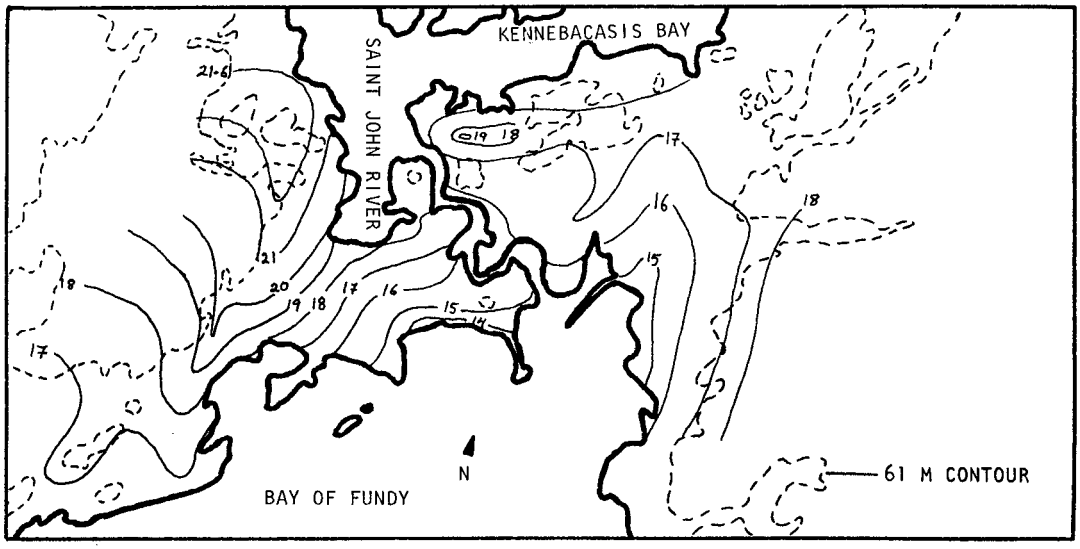


Figure 6.—Surface isotherms at 1100 on 18 July 1974, showing the effects of topography. The areas enclosed by the dashed lines (the 61-m contour) have an elevation above 61 m.



temperature distribution. The dashed lines show the 61-m contour. Two dominant hot spots can be observed, one in the upper center of the picture, and the other directly to the left of it. Each is in a valley protected from the sea breeze to the south. The inward thrust of the sea breeze can be seen to the right of the plot where it lines up reasonably well with the valley. On the west, the more complex topography tends to obscure the early effects of the sea breeze.

CONCLUSION

This technique for obtaining surface isotherms is both simple and inexpensive to operate. The results can be used to aid in land-use planning on several scales. Areas that have high summer daytime temperatures and are near water are naturals for good tourist-industry development, offering swimming and boating. Industrial development normally associated with coastal regions should be located in areas where gaseous effluent will not be carried inland to residential areas by the sea breeze on clear afternoons. Individual people can also use this type of information in a qualitative manner in choosing general areas of habitation.

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The Urban Heat Island in Akron, Ohio

by FRANK P. MARTIN *and* GRACE L. POWELL, *respectively weather service specialist, National Weather Service, Akron, Ohio; and associate professor of geography, University of Akron, Akron, Ohio.*

ABSTRACT.—Data gathered by automobile traverse were used to describe the urban heat of Akron, Ohio. Observations were made at 2100 or 2200 EST on four nights—17 April, 11 July, 10 October, and 2 January. Weather conditions not conducive to heat-island development were avoided. Temperatures in the center of the heat island were 6 to 14°F warmer than rural areas outside the city. The heat-island center was always over a mixed residential/commercial area. Topographic influences were apparent in the heat-island pattern.

MUCH HAS BEEN WRITTEN about the micro-climatic variations that have been found in some urbanized areas and hence have been assumed to exist in other urban centers as well. The most commonly documented urban impact on climate has become widely known as the "heat island."

Factors contributing to a heat island's existence are integral parts of urban areas — pavement, brick, concrete, asphalt, and other stone-like building materials; high volume of motorized traffic; large concentrations of heated and otherwise energy-serviced buildings; and industrial complexes. Despite the near certainty that a heat island can be identified in almost any urban center, the precise location and the magnitude of its development are anything but certain. The factors bearing on the way in which heat islands develop are reviewed as the heat island in Akron, Ohio, is examined here.

METHOD OF DATA COLLECTION

Data for this study were collected on the nights of 17 April, 11 July, and 10 October 1972 and 2 January 1973, using the automobile traverse method similar to that used by Hutcheon *et al. (1967)*. Weather on the days chosen for the investigation varied significantly enough throughout the days (and during the time of the traverse runs) to assure a fair representation of meteorological conditions. However, days with strong winds, cloud cover, and precipitation were avoided for data collection because these conditions weaken or eliminate heat islands. Week nights were chosen for investigation because Mitchell *(1953)* showed that increased human activity through the week days cause warmer urban temperatures than those that occur on weekends.

RESULTS

As may readily be seen (figs. 1 to 4), the center of the heat island in Akron formed over the same area on all four occasions — approximately 1.5 miles northwest of the central business district (CBD). The intensity of the heat island is indicated by the temperature differential between the edge of the city and the heat island center. The intensity varied with the season: 9°F in spring, 6°F in summer, 14°F in autumn, and 7°F in winter.

The center of Akron's heat island is located over a mixed residential-commercial land-use area. The commercial activity is located in relatively low-profile buildings with large paved parking areas. These low-profile buildings have very little shadowing effect on each other; hence considerable solar radiation

Figure 1.—Akron's heat island location 2200 EST, 17 April 1972.

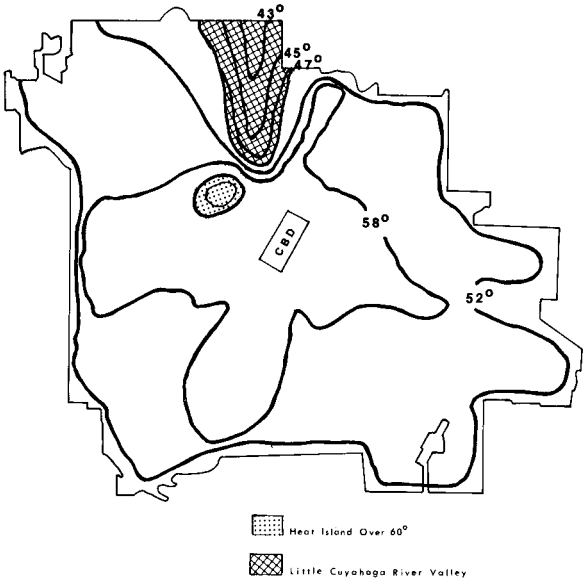


Figure 2.—Akron's heat island location 2100 EST, 11 July 1972.

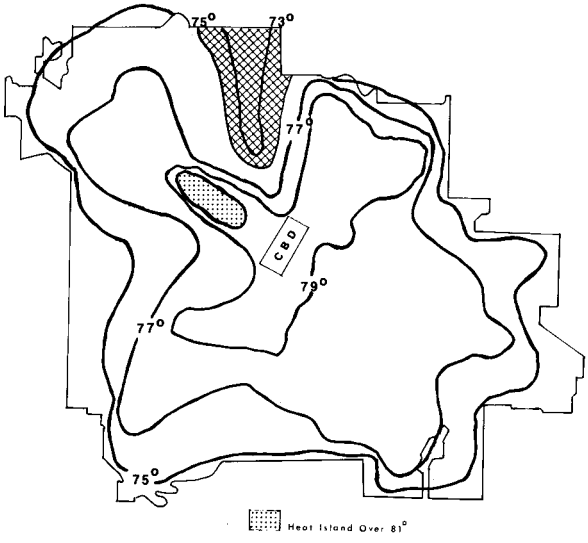


Figure 3.—Akron's heat island location 2100 EST, 10 October 1972.

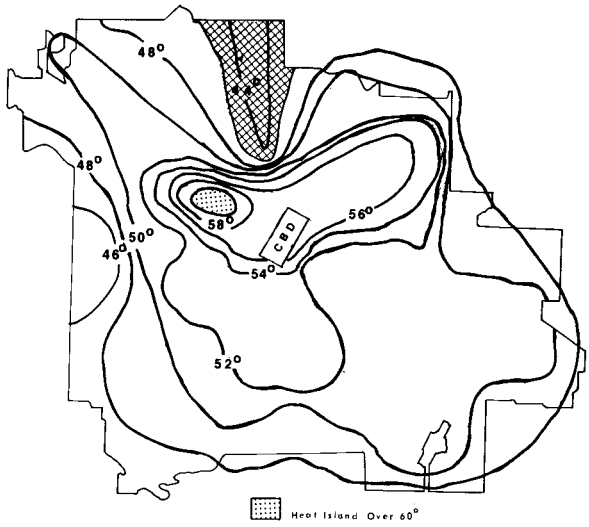
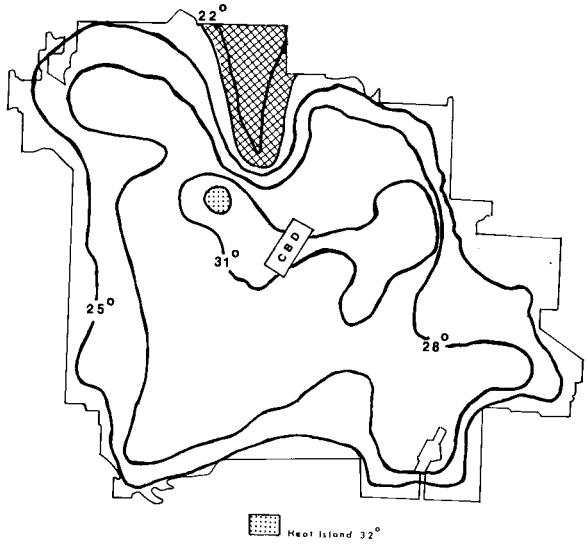


Figure 4.—Akron's heat island location 2200 EST, 2 January 1973.



is absorbed by them during the day. After sunset, the stone-like surfaces conduct heat to the urban air-causing excess heating.

The housing at the center of the heat-island area varies from modern multi-storied apartment houses to large frame (and a few brick) houses that are about 60 years old and have been converted into apartments. The average number of residents per apartment is three.

This concentration of apartments has resulted in the area having the second highest housing and population density in the city of Akron. The areas of the city that have the highest housing and population density are located on low-lying ground, and cold air drainage prevents the formation of a heat island over these high housing/population density areas.

The University of Akron Laboratory for Spatial and Cartographic Analysis has produced maps of Akron, using 1970 Census Data, which show the sections of the city with population density of 20 to 25 persons per acre and 6 to 10 houses per acre (figs. 5 and 6).

These population and housing variables are important, since human and animal metabolic heat, and waste heat from space heating (and cooling), all contribute heat to the urban atmosphere.

In addition, the heat-island center is located over relatively high ground that causes cold air to drain away from that area. The heat-island center is approximately 100 feet higher than the surrounding ground.

DISCUSSION

Since heat-island formation is due to the impact of man, it follows that heat islands can be reduced, intensified, or possibly eliminated by man's effort. Investigation into how to eliminate a heat island should become an area of research after its location and intensity is known. Bach *(1972)* showed that wise land use can decrease the effect of heat islands.

Some may question why this type of investigation should become important and a source of intensive investigation. The answer is simple — heat islands are killers. Clarke *(1972)* and Buechley *et al. (1972)* have shown that the combination of increased heat and humidity of urban areas produces thermal stres-

Figure 5.—Housing density in the heat island in Akron, Ohio (1970 Census data).

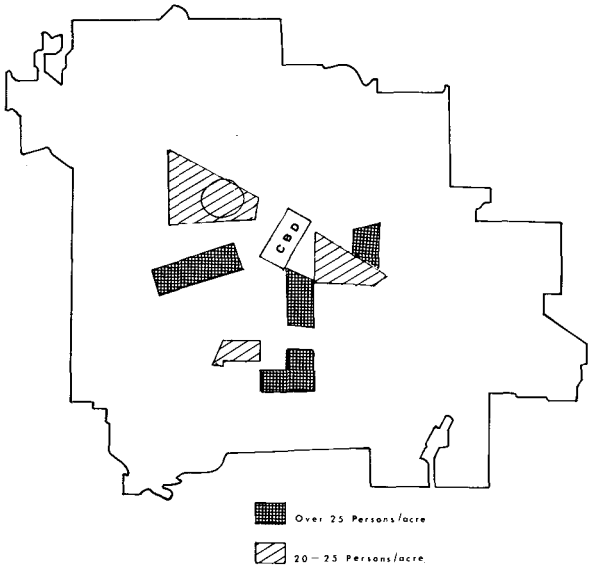
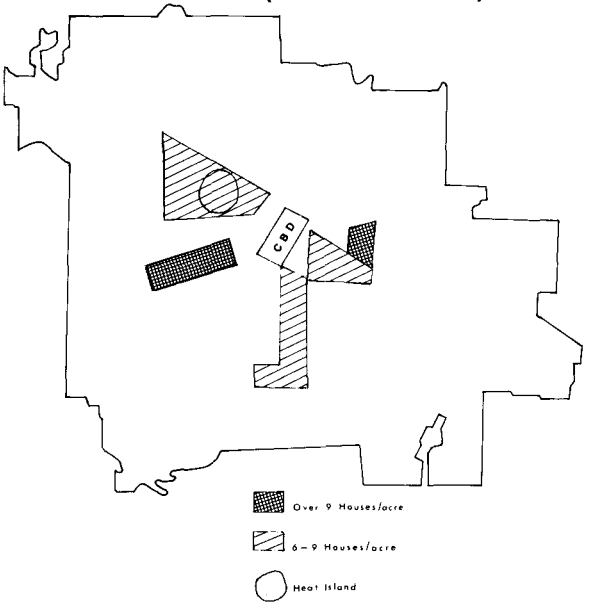


Figure 6.—Population density in the heat island in Akron, Ohio (1970 Census data).



ses, particularly at night among the poor and elderly, who are the predominate economic and age groups that live in the central cities.

These thermal stresses are a significant factor in causing urban mortality rates to be much higher than rural or suburban mortality rates during heat-wave conditions. The thermal stresses are produced because there is virtually no relief from heat and humidity in the urban areas at night due to the heat-island effect and the lack of air conditioning among the poor and elderly. However, in the rural and suburban areas, relief from thermal stress occurs once nocturnal cooling begins.

Just how significant this death rate can be was indicated by Bridger and Hefland *(1968)*. They studied the St. Louis, Missouri, area for July 1966 and found that, although the corporate limits of the city (at that time) contained only 32 percent of the metropolitan population, 85 percent of the heat-related deaths took place within the corporate limits. The urban death rate was 5.5 times as great as the rural death rate for the same time period. Other studies have indicated similar results.

CONCLUSION

Despite the prevalence of heat islands as urban climatological phenomena, their location, nature, and magnitude cannot be inferred on the basis of city size, industry mix, and housing density alone. Local climatological and physiographic conditions must also be considered. The net result is that, at least until much more work is done, each urban situation must be treated as a unique case. As this study has shown, careful and precise measurements need to be taken within an urban area to determine the nature, extent, and magnitude of heat islands.

The heat island in Akron is the result of the interaction of four variables: elevation, land use, housing density, and population density. A significant change in any of the four could cause the heat island to be weakened.

City planners should take such matters as those discussed in this study into consideration when making plans for urban expansion or building within the city, because whatever they do affects the microclimate. However, it seems that most planners have little knowledge of microclimatology. Unpleasant urban climates reflect both the lack of planning and the lack of knowledge of microclimatology.

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MICROSCALE METEOROLOGY IN METROPOLITAN REGIONS

Washington's "Free" 300-Station Microscale Weather Network

by THOMAS BLACKBURN, *meteorologist, Planning and Requirements, Office of Meteorology and Oceanography, National Weather Service, Silver Spring, Md.*

ABSTRACT.—This article is intended to encourage those planning to conduct meso- or microscale weather studies to supplement their sophisticated observing techniques and equipment with low-cost observations taken by volunteers. Such observations can often show high benefits per unit costs in expanding the geographical area of study, increasing the density of observations, or in verifying the validity of urban study findings. Techniques used in recruiting and sustaining the 300-station volunteer Washington, D.C., Network are described.

DATA FROM APPROXIMATELY 320 precipitation - observing sites within a 25-mile radius of downtown Washington, D.C., are recorded after each occurrence, under the sponsorship of the Washington National Weather Service Forecast Office (WSFO). About 150 of these sites record maximum and minimum temperatures once daily, and many report additional meteorological events of interest, such as high winds, hail, thunderstorms, ice storms, and floods. Observers mail in their reports at the end of each month, and a few report real-time weather events to the WSFO via recording telephone.

COSTS OF OPERATING WASHINGTON NETWORK

All observers supply their data to the Washington Network without pay, and the majority of them purchase and pay for their own equipment. The rest are participants in separate networks sponsored by the federal and county governments.

Bookkeeping, tabulation of the reports, and preparation of a monthly weather summary are done in off-duty time, largely by Stephen Flood and the author. Flood also puts in a limited amount of time during slack periods in his NWS work schedule. Many of the observers have also contributed their time generously.

There are two NWS cost items to the Washington Network. One is the printing of the Metropolitan Network Monthly Reports (fig. 1) costing less than 5¢ each. The reverse side of this form contains the mailing address. Mailing is free, using government franking privileges. The second cost item is the printing of the monthly weather summary, which averaged $43 per 8-page issue in 1974. Franking privileges are used to mail this free to volunteer observers and a few others.

Figure 1.—Metropolitan Network monthly report card, used by volunteer observers to record and mail observations.

WS FORM F-54
(9-72)

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMIN
NATIONAL WEATHER SERVICE

METROPOLITAN NETWORK MONTHLY REPORT

Please mail by fifth day of month

STATION NUMBER	MONTH	YEAR

NAME

TIME OF OBSERVATION

TEMPERATURE | PRECIPITATION OR ☐ AFTER PRECIP ENDS

DAY	TEMPERATURE PAST 24 HR. MAX.	MIN.	OBS	PCPN HNDTHS	SNOW TENTHS	REMARKS
1						
2						
3						
4						
5						
27						
28						
29						
30						
31						
TOTAL						

☐ *Check if more cards are needed*

'S FORM F-54 (9-72)

NETWORK INSTRUMENTATION AND DATA EXCHANGE WITH OTHER NETWORKS

Of the 320 rain-gage sites, 40 are recording and 20 are NWS standard 8-inch. Of the 40 recording gages, 34 are operated by county governments comparing rainfall vs. runoff and flooding relationships between urbanized areas and the outer suburbs where urbanization is planned. Most of the other recording gages are located at NWS and military weather stations at airports. The 8-inch gages are operated mostly by stations in the NWS climatological network. The network has an additional 20 or so clear plastic cylindrical rain-snow gages having an 11-inch capacity, and 240 wedge-type plastic gages with a 6-inch capacity. These are purchased by observers both for participation in the Washington Network and for their own use; they cost about $10 and $2.50, respectively, in 1975. These are signi-

ficantly below retail, thanks to bulk purchases.

Maximum-minimum thermometers are of the U-shaped type, except for about 30 at NWS and military weather stations and in the NWS climatological network. The U-shaped thermometers were bulk-purchased for about $9 in 1974.

Temperature and rainfall data from climatological, county, and federal government stations are freely shared with the Washington Network; and summarized data from the Washington Network are shared with those operating the government networks.

POTENTIAL OF UNPAID VOLUNTEERS IN SUPPLEMENTING MICROSCALE STUDIES

The main purpose of describing the Washington Network is to suggest usage of the same type of data to augment other types of meso- or microscale studies. Suggestions for the establishment and maintenance of such networks are offered later.

It would be difficult to justify establishing much of a volunteer network to supplement short-period studies, such as 2 or 3 nights of temperature traverses, due to the time and effort required to establish it. However, the value of volunteer networks increases as the length of the period of the microscale study increases. Some suggested microscale studies using volunteer observers are discussed below.

Studies of the Influence of Urbanization or Terrain on Precipitation Patterns

Application of the low-cost Washington Network concept is most obvious as a supplement to urban precipitation studies. The appeal of volunteer observations lies in the use of a mix of simple and complex observing systems. For example, instead of setting up a network of recording rain gages about 2 miles apart, every other station in this 2-mile grid could consist of a simple rain gage operated by a volunteer. Use of the low-cost gages at about half of the planned observing sites would cut field instrumentation costs significantly. It is doubtful that estimations of rainfall rates and measurements of storm totals would suffer unduly from this substitution, even in the case of stationary thunderstorms with intense isohyetal gradients, especially if digital radar data were available for the study area to assist with analyses.

A correlary use of volunteer observers would be to intersperse these between recording gages installed at the preplanned locations, as a means of increasing data density and hence, analysis accuracy. This type of use is particularly apropos for studying rainfall-runoff relationships (and for improving real-time flash-flood warning capabilities) over small drainage basins, or over somewhat larger basins lacking digital radar within a reasonable distance.

Urban-Heat-Island Studies

One of the main goals of urban temperature studies is to establish relationships between temperature and nonmeteorological factors such as terrain, degree of urbanization, and vegetation (TUV). Empirical relationships established between these in one metropolitan area are most beneficial if they are exportable to other areas.

The establishment of reliable TUV relationships to temperature over any sizable area can be quite difficult using temperature traverses alone, due to short-period temperature changes or the number of simultaneous traverses needed. There are two means by which volunteer observers may contribute. First, they can be informed in advance of the times of planned temperature traverses, in order to coordinate their readings. However, many traverses are conducted during inconvenient hours (at night). This problem is partly overcome by the second method, which uses volunteers having maximum-minimum

thermometers. Readings by the volunteers need not be made at specific times if the traverses are made at or near times of maximum or minimum temperature.

An additional advantage of volunteers is their capability of taking readings over extended periods of time — a procedure that is usually impractical for temperature traverses. Extended records are beneficial not only for obtaining long-term averages, but also for getting several sets of samplings under different combinations of wind speed, cloud, and snow cover.

Pollution-Sampling Networks

Volunteer pollution observers judiciously scattered over a city could provide a low-cost yet valuable supplement to more sophisticated pollutant-measuring networks. Volunteer observers could either retain samples of their rainfall for certain types of air (or water) pollutant analysis, or expose other types of pollution collectors to the air.

Recruiting procedures depend on the type of sampling employed. Small, light samples could possibly be mailed after exposure, while the larger ones should be taken to a common collection point. For the latter, recruiting might be concentrated within a given office building, where volunteers could drop samples off at work.

Selection of pollution observers from pre-existing temperature or rainfall networks offers about the best chance of obtaining people of proven reliability, likely to be interested in participating, and capable of following instructions. Random recruiting can often result in volunteers lacking these qualities.

Relationship of Urban Temperature Patterns to Vegetation and Length of Growing Season

Costly temperature-measuring devices need not be relied on entirely to determine the effect of vegetation on urban temperature patterns and vice versa. Much can be learned by comparing maximum and minimum temperatures taken by volunteers in builtup vs. forested areas. These same observers could also report the impact of weather and urbanization on plant life, such as flower-blooming dates and frost, fungus, and pest damage.

Washington's annual Cherry Blossom Parade would usually have to take place 3 weeks later if it were held in the northern part of the suburbs, yet still inside the Beltway. Volunteer observations have shown the growing season to be 3½ months longer in the warmest part of the heat island than in the outer suburb valleys 25 miles away in two of the past 4 years, despite variations in elevation of only 500 feet.

The increased evaporation rate in the heat island is probably the main reason the downtown Arlington Army-Navy Country Club requires more watering than the rural golf courses.

POTENTIAL SOURCES OF FREE OBSERVATIONS

There are two basic sources of free observations. One consists of existing observing sites and the other of potential new observers. Either source may be surprisingly easy to tap, and may provide more data than seem necessary in some areas. The acceptance of some redundancy can help compensate both for what might be less accurate observations and (in the case of extended-period studies) for dropouts and temporary observer absences during summer vacations.

Pre-Existing Observations

The following list includes potential sources of pre-existing observations. The number at the end of each source indicates the number of that type of observation in the Washington Network.

1. Airports (military or civilian) handling scheduled traffic. These take observations hourly. There are seven of these in the Washington Network,

each of which submits monthly summaries.

2. NWS climatological stations, or USDA experiment stations etc. recording maximum and minimum temperatures and daily precipitation (about 15).
3. Networks of recording rain gages operated by county governments or the U.S. Geological Survey (about 34).
4. Golf courses (5), farmers (15), utilities — electric and natural gas (5), who have an economic stake in weather.
5. Employees of the NWS, Geological Survey, or any other federal or local agency having an interest in weather (about 80).
6. Those having weather as a hobby, or interested in temperature and/or rainfall for lawn or garden growth and watering needs, or school earth-science departments and college meteorology or geography departments (about 50).

More than 200 of Washington's 320 observations were obtained from the above pre-existing sources. They provide the advantages of more weather knowledge and a lower turnover than in newly recruited observers, whose enthusiasm is more likely to wane soon.

New Observations

Sources of new observers would include those in (d) through (f) above who are not yet participating, the general public, perhaps 4-H or Future Farmers of America (if suburban data are needed), and retired people, who often are looking for a meaningful hobby useful to others.

Recruiting Suggestions

Several methods of finding existing observers and recruiting new ones have successfully been employed in Washington, and should be applicable elsewhere. Some are listed below.

1. Contact airports and NWS climatological stations. These must generally be contacted individually and supplied with envelopes in which to mail their reports. Names and addresses of climatological stations may be obtained from NWS substation network specialists, generally located at NWS forecast offices.
2. Put notices in local weekly or monthly news bulletins distributed to an organization's or business establishment's employees. One such notice put in a National Bureau of Standards weekly bulletin resulted in 30 new Washington Network observers.
3. Set up model weather-observing stations at science fairs, county fairs, or state fairs. One of the most successful recruiting efforts was at an NWS open house held outdoors and visited by many Washington-area school classes.
4. Contact weekly or daily newspapers likely to be interested in your project. Try to assure that the article prominently emphasizes your desire to recruit observers — a fact often buried toward the end of articles carried in Washington papers.
5. Have a television station prepare a short filmstrip describing your project, and have it shown along with the regular TV weather forecast. Many amateur meteorologists are avid watchers of the TV weather programs.
6. Ask scientifically oriented organizations to permit you to request volunteers via their monthly meeting announcements. An announcement in the local American Meteorological Society monthly bulletin drew several volunteers. Notices in local publications of the American Association of Retired People (AARP) should prove fruitful, at least for warm-season observers.
7. Make house-to-house or farm-to-farm visits. Though this method may seem difficult, these visits let you know exactly where in your network each

new station is located, its proximity to vegetation, valleys, and pollution or heat sources, and each station's instrument exposure.

A stock of weather equipment should be maintained for mailing or personal delivery to observers who do not have their own. Rain gages and maximum-minimum thermometers are purchased in bulk at reduced prices for distribution in the Washington area. The 11-inch capacity gages are purchased in lots of six for about $10 each, postage paid, from the Lake Region Rehab. Ind., Inc., P.O. Box 404, Fergus Falls, Minn. 56537, telephone 218-736-5668. The 6-inch capacity wedge gage comes from the Tru-Chek Rain Gage Div., Edwards Mfg. Co., Albert Lea, Minn. 56007, telephone 507-373-8206. These may be purchased for about $2.40 each plus shipping, in lots of 20. Maximum-minimum thermometers are purchased at a discount through one of our golf-course superintendent volunteers.

MAINTAINING THE INTEREST AND COOPERATION OF VOLUNTEERS

The retention of unpaid volunteers in extended period studies is highly dependent on frequent feedback showing the fruits of observers' efforts. This is achieved in two ways in the Washington Network. First, a letter of thanks is sent out annually with each new supply of weather-reporting forms; and second, observers receive copies of the monthly Metropolitan Climatological Summary (MCS). The summary contains: (1) analyzed maps of individual storms, on which each observer's rainfall amounts are plotted; (2) maps on which average and extreme maximum and minimum temperatures are plotted for each station; (3) a table listing each observer's name, station number, and monthly (and sometimes maximum 24-hour) precipitation; and (4) observer's comments and descriptions of the month's weather events both in the descriptions of individual storms and a summary of the highlights of the month's weather events.

The success of the Washington Network in retaining the cooperation of its volunteers may be attested to by the fact that there has been no recruiting since 1972, during which time the Network has suffered a net loss of active volunteers of only about 50 (from about 370 to 320). Another 75 or so dropouts have been matched by word-of-mouth volunteers.

Figure 2 shows a sample MCS storm analysis. Note the use of observers' comments.

QUALITY CONTROL

Quality control covers both instrument accuracy and instrument exposure.

Instrument Accuracy

Rain-gage accuracy should be satisfactory if gages are of equal or better quality to those described above. Even the simple farm gages having no magnification are useful in the absence of other readings, provided precise rainfall amounts are not required. The U-shaped type of maximum-minimum thermometers should not be used unless it is possible to adjust upward or downward the maximum and minimum temperature scales independently of each other as may be needed to eliminate errors. This requirement excludes thermometers with scales printed on the frame. If money is of secondary importance, separate maximum-and-minimum thermometers meeting NWS specifications are preferred.

Washington Network thermometers are mostly of the U-shaped type with independently adjustable scales. Calibration is accomplished by placing all thermometers on a table in a room having no heat and cold sources and by circulating the air rapidly by a fan. Five separate sets of calibrations are run against a precision thermometer marked to the nearest 0.2°.

Figure 2.—Analysis of Washington area rainfall 25-26 June 1975. Solid lines are isohyetals of equal rainfall amounts, drawn at 1/2-inch intervals. Shaded areas received more than 2.50 inches of rain. Note use made of observers' comments in text at top.

RAINS OF JUNE 25-26

SYNOPTIC SITUATION AND EFFECTS

A weak "back door" cold front (a front coming in from the NE instead of NW) drifted southward through the DC area on the afternoon of the 25th, setting off heavy thunderstorms and locallized violent winds and some hail, all to the northern Va. and western Montgomery County areas of the NCA (National Capital Area). Then, after midnight, the heaviest rains of the year struck the Beltsville and northern Gaithersburg (Washington Grove) areas, setting off heavy flash flooding. Fortunately, these came at a time of day when little inconvenience resulted.

EVENING STORMS - HAIL AND WIND

Storms first formed about 4:30 p.m. in western Montgomery Co. and adjacent areas of northern Loudoun County. Goldstein (121) reported .24" rain by 5pm (and another .44" mostly between 6 and 7 pm). Seebode (318) heard thunder from this storm before a new storm formed overhead, bringing him up to 1/2" hail for 20 minutes and 1.44" of rain between 5:16 and 6:38 p.m. Swindler (321) also reported hail, as well as 45 mph winds.

Soon after this, new storms developed suddenly over Dulles Airport (403) eastward to the Vienna-Fairfax City areas, dumping over 2" of rain on both locales. High winds (from the storm's downdrafts) swept through a small area of western Fairfax City, where Adams (618A) reported strong gusty north winds, a corn crop flattened, extensive tree damage throughout the Cobbdale area, and heavy flooding, with 2.22" rain from 6:40 to 8 p.m. Weber (618) noted gigantic oak trees downed along route 123 and Hunter Mill Rd., and Atkins (in Cobbdale) lost several trees and suspected tornadic activity. Merserau (619) was soused with 2.25" of rain in an hour. MacNulty (927) observed the next big storm getting underway over and south of him around 8 p.m.

STORM CELL MOVEMENT

While the active thunderstorm cells were developing (not moving) southward through Fairfax Co., the upper layers of the stormclouds moved eastward, sprinkling much of the rest of the NCA with gentle rains. A multitude of observers commented on the long periods of the evening during which they heard distant and eventually overhead rolls of thunder, but experienced only light rains-after 1-2 hours of thunder.

POST-MIDNIGHT STORMS

To most of us it appeared that the thunderstorm activity had ended for the night, as thunder diminished by late evening. Not so. Shortly after midnight very localllized but drenching storms struck Beltsville, Layhill and Gaithersburg, with an abundant electrical display. Oliver (268) reported nearly continuous lightning and rain beginning 10 p.m., and ending by 5 a.m., with 3.45" rain. Nealis (267) reported "severe electrical storms from midnight to 2:30 a.m., streets flooded," and 5.88" of rain. Fisher (269) was also near the center of the "violent thunderstorm after midnight." In all, four stations received over 5" of water in the Beltsville area, while Whitcombe (35) recorded 5.60" in Washington Grove.

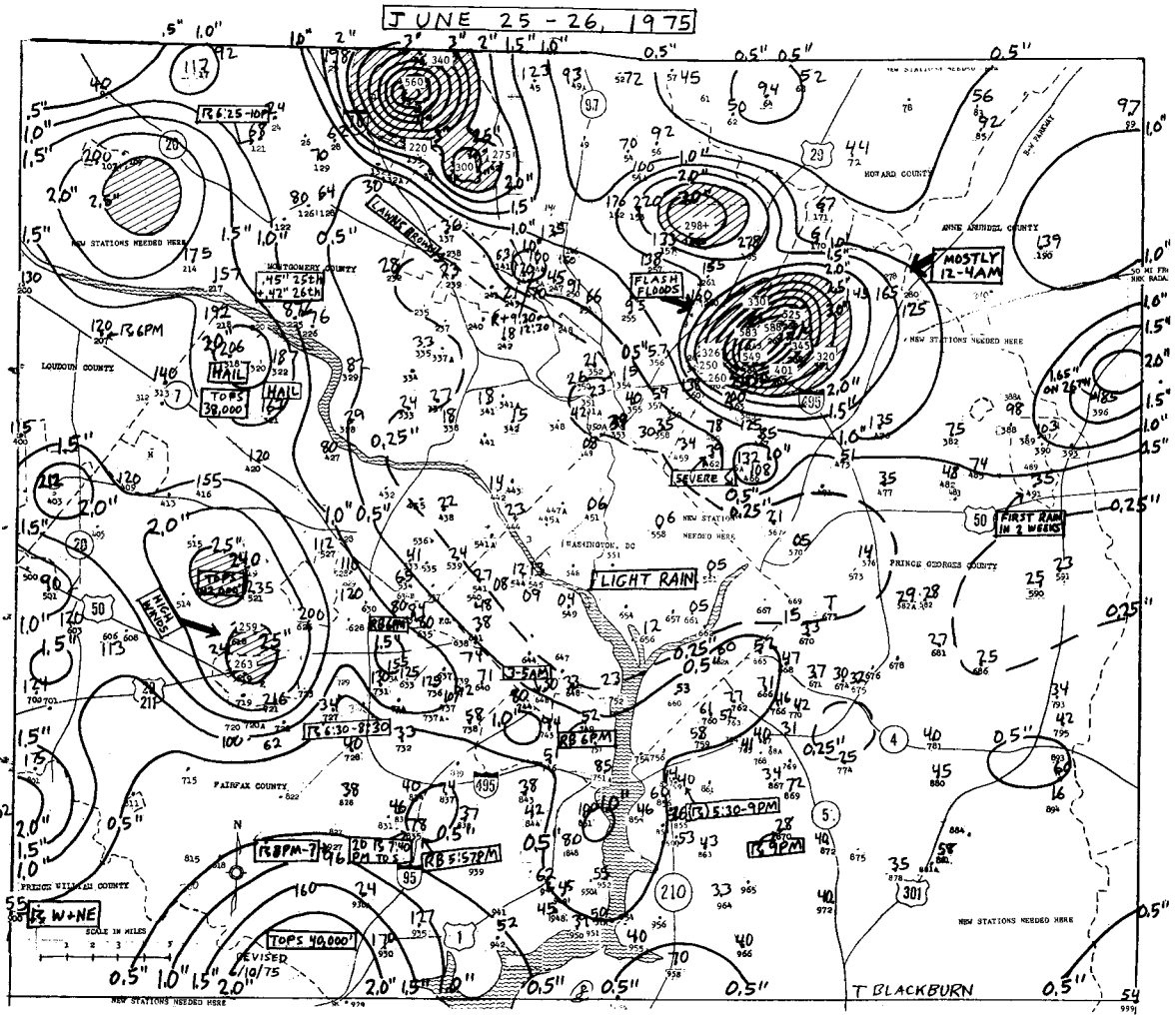
MIDNIGHT STORMS MORE LOCALLIZED AND PERSISTENT

While the evening storms in Va. moved around somewhat, thereby spreading out the area over which rains fell, the Beltsville storms had a net of zero motion, dumping all their rains in essentially the same spot. The cause of the change was apparently an increase in the low level easterly wind, that seemed to neutralize almost exactly the westerly winds at higher levels. Rainfall isohyetals were thus much more tightly packed than during the previous evening. The Beltsville storm was amazingly persistent, resulting in the following hourly amounts at Beltsville Plant Industry Station #7 (367):

12-1 a.m.	0.98"	2-3 a.m.	1.60"
1-2 a.m.	1.47"	3-3:40a.m.	1.27"

Note that the rate of fall per hour at 367 was less than in the Virginia storms, but the deluge persisted much longer.

Continued (see July 11-13 storm for conclusion of text)



Instrument Exposure

Instrument exposure can be checked at the time the instrument is installed, if done in person. Most new Washington Network instruments have been mailed out, and have had no such inspection. To compensate for this, detailed site-selection instructions are sent, together with occasional reminders in the MCS.

Inadequate rain-gage exposure may show up in readings inconsistent with adjacent data for rains having negligible isohyetal gradients. Such consistency checks, however, are only the poor man's substitute for on-site inspection.

Only about a fourth of the thermometers are located in official NWS "Cotton Region Shelters." The rest are usually mounted on the shady side of a structure, some with a small white shield installed on one side as protection from morning or evening sunshine.

Direct exposure to sunshine can usually be detected by plotting and comparing maximum temperatures on a clear windless day. Similar plots on uniform temperature cloudy days will often show up stations whose temperatures do not appear to fit the expected isohyetal pattern.

PROCESSING VOLUNTEER WEATHER OBSERVATIONS

The most obvious problem with the acquisition of a large volume of data regards how it is to be processed. Several day's work have been accomplished in an afternoon by assembling several of the volunteer observers to plot the past month's Washington Network rainfall amounts. One person reads the daily amounts from each monthly report, while each of the other participants plots the amount for his assigned rainfall date on a blank base map. Maximum and minimum temperature plots can be handled by the same type of group effort.

Initial analyses of the plotted data can be entered by the participant on a transparent overlay. The smoothed final product requires some training, however.

Observers have been very cooperative in totalling their own temperature and rainfall data.

REPORTING WEATHER AS IT OCCURS

Observers in the Washington Network have three options for telephoning weather data to the NWS Forecast Office as it occurs.

1. *Live Conversations.* The observer calls the forecaster, who takes the message live. This is used for urgent (severe weather) messages.
2. *Recorded Messages.* Significant, but not severe weather is recorded on a Code-a-Phone and played back by the forecaster once per hour, or more frequently during bad weather.
3. *Touch Tone.* Observers having touch-tone telephones send messages directly to a computer, which converts the tone signals first to a printout of the numbers sent (optional), and second into a formatted, printed plain-language message. This method can eliminate answering the telephone and manual computer input. However, it is not for the low-budget study, as a program must be written to decode the tones; a computer terminal is needed to display the observations; etc.

POSSIBLE USES FOR URBAN STUDY RESULTS AND OBSERVATIONS

There are a few uses of urban studies and observations that could be applied to improve the accuracy of daily forecasts, either by the NWS, or by private meteorologists, the latter being the more likely users in the immediate future. The NWS, however, has increased its interest in making detailed short-period forecasts to the point where the telephoned observations received are now used to issue hourly Washington metropolitan-area weather summaries and forecasts. Also, a special Summer 1975

project used data from volunteer observers on boats and at marinas to prepare similar detailed forecasts and warnings for Chesapeake Bay boaters. The latter observations are sent by touch-tone telephone.

Four possible uses of urban studies or observations are listed below.

Urban-Heat-Island Studies

Studies of urban temperature patterns could be used, for example, to show expected temperature *deviations* in different parts of the city from the official minimum temperature forecast. The change in the daily deviation would depend on factors such as wind, cloud, and snow cover. A sample procedure for doing this is shown below.

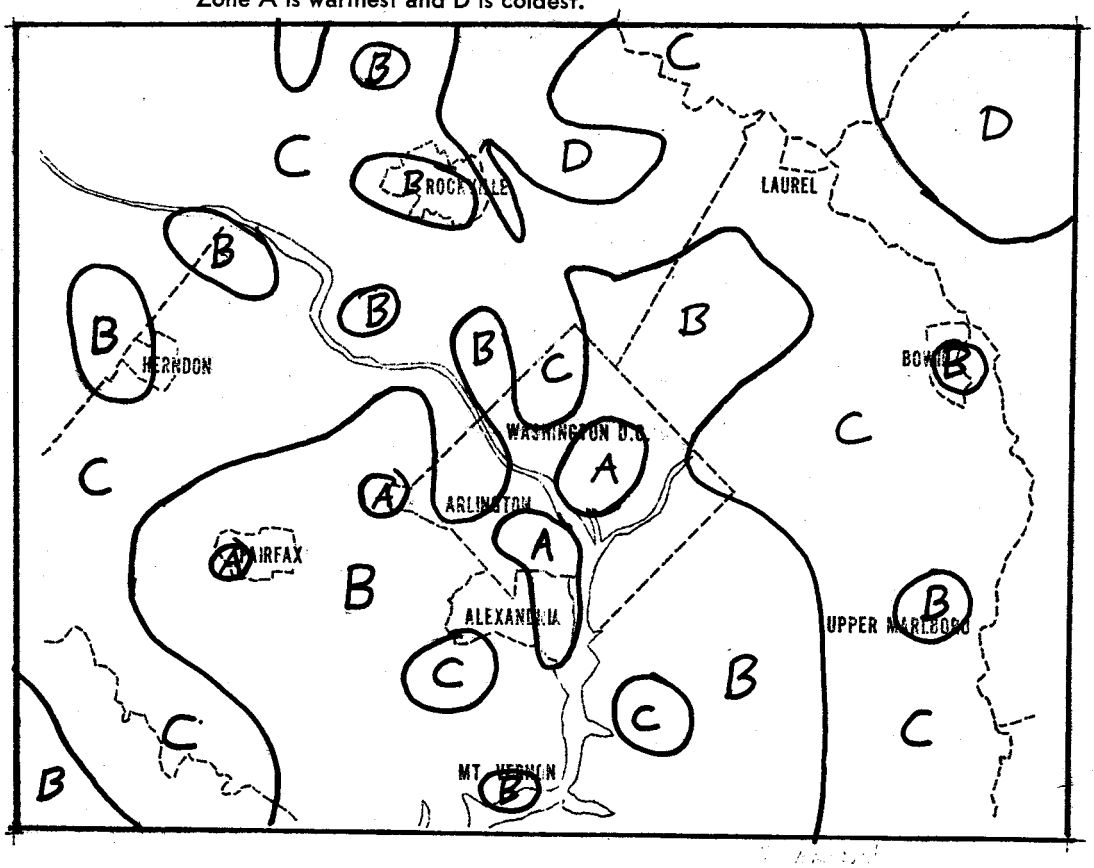
1. Take a metropolitan area for which isotherm patterns (at times of minimum temperatures) have ben determined, and divide it into about four temperature zones. Label the warmest and coldest zones Zones A and D, respectively, with Zones B and C having values between A and D.
2. Determine weather conditions associated with both the greatest and least geographical urban temperature variations, and about two other stages between these extremes. Call these conditions 1 through 4, condition 1 being weather associated with the least variation.
3. For this simplified example, assume that zones A and D will encompass the warmest and coldest areas, respectively, in each of conditions 1 through 4 and regardless of wind direction or any other variable.
4. Assign average temperature *departures* from the central heat island temperature for zones A through D for each of conditions 1 through 4. Zone A would be assigned a departure of 0°. Temperature *ranges* could be used instead of averages for each zone, in which case zone D might have a range from —14° to —18° instead of an average of —16° under condition 4.
5. Assume the official minimum temperature forecast for the city to be the minimum expected in the heat island. For example, a forecast of "low tonight 45° in the city of 30° in the colder suburbs" might mean minima of 45° in zone A and 30° in zone D, and average departures would be 0° and —15°, respectively.
6. Find a television weathercaster willing to read the official forecast, modified by the zone B, C, and D temperature adjustments. This assumes he or she is willing to forecast which of conditions 1 through 4 will apply.

Figure 3 shows a rough approximation (and gross simplification) of zones A through D for the Washington metropolitan area. The area shown is 45 miles wide — probably much larger than is needed, and the data base consists entirely of volunteer observers. Under conditions 1 and 4 the temperature differential between Washington's *adjacent* zones are about 1° and 5° F, respectively, although with snow cover, no wind and clear skies (which seldom occurs more than once per year), temperatures have varied by 26°.

Air-Pollution Distribution Forecasts

Should it be determined useful to predict which parts of a metropolitan area will suffer the severest pollution in the next day or so, studies of the relationship of low-level winds and other factors to pollution distribution could be used to make such predictions. The forecast procedure would be somewhat like that for temperature distribution, except that emphasis would be on the distribution and concentration of pollutants over the metropolitan area under different wind and lapse-rate directions.

Figure 3.—Smoothed temperature zones for Washington area. Zone A is warmest and D is coldest.



Improvement of Short-Period Metropolitan Area Forecasts and Warnings

While volunteer observations have been used extensively in tornado spotter networks, their use in daily forecasts and warnings has been rather limited.

Real-time urban network observations can be a tremendous aid in the detection and hence the issuance of short-period hail, heavy rain, flash-flood, local fog, snow, and wind warnings and forecasts. Reports can also assist in the issuance of detailed hourly synopses and forecasts of metropolitan weather conditions. Knowledge of which sections of a city will receive rain during the next hour or two can be very useful to people engaged in activities such as boating and construction.

Real-time ...erature reports received on days with precipitation accompanied by temperatures near freezing can be useful in the optimum deployment of snow-removal crews from above-freezing to below-freezing areas of a city. In the case of freezing rain, travelers advisories can be limited to below-freezing areas. Volunteer observations can also assist in monitoring the movement of the rain-snow line.

Improving Summertime Probability of Precipitation (POP) Forecasts

POP forecasts for metropolitan areas verify at a single observing point. Thus, if measurable rain fell at the verification point, a POP of 80 percent would have verified with only a 20 percent error (a 100 percent POP would have had no error) even if three-fourths of the rest of the metro area remained dry.

During seasons when rains tend to be spotty, I would like to see the POP verified against 5 or 10 evenly spaced observing sites, which could be operated by volunteers at essentially no cost. If 6 of the 10 stations reported precipitation, the best POP would have been 60 percent.

Verification procedures would have to be redefined to indicate the percentages of the metropolitan area expected to have measurable precipitation, rather than the POP at any given spot. Hopefully, this redefinition would increase the credibility as well as accuracy of summer forecasts. For example, while the radio listener now scorns a 30 percent POP forecast if he's in a downpour, he's more likely to believe it if it's defined to mean only 30 percent of the *area* will have rain.

An alternative to the rain-gage network would be radar determination of rainfall coverage. This is quite promising. The only problem noted in the Washington area is that the radar precipitation area often appears to extend 2 to 3 miles beyond the actual rain area. This problem should not be unsolvable.

Let's Make Quantitative Precipitation Forecast (QPF) Verification More Realistic

QPF's are verified for accuracy at a given point (the official metro area observing site). Though this method may be satisfactory for prolonged nonconvective rains, it can be gravely misleading during thunderstorm situations.

Rainfall amounts from the same 5 to 10 sites proposed for POP verification could be averaged to obtain a value more representative of the metropolitan area than single-station verification.

A second QPF verification scheme would use rainfall depths determined by radar. However, the accuracy of radar-determined convective rainfall amounts is such that rain-gage readings are needed to calibrate the radar. Nevertheless, radar-determined amounts alone should be preferable to single-station QPF verification.

Until the QPF verification method is changed, it will be difficult to evaluate QPF accuracy, as is needed before significant additional forecast improvement is possible.

Injury and Damage Claims

Lawyers and insurance companies are frequently in need of more localized meteorological data than that available from the official observing site. They are quick to question a wind- or hail-damage claim if the official site had none. A lawsuit resulting from a fall on a snow-covered sidewalk may be justified, but will be difficult to support if the official station reported only rain and above-freezing temperatures, and no other data are available. Lawyers and insurance adjusters frequently request data for a particular suburb of Washington, D.C.

Structure of the Microclimate at a Woodland/Parking-Lot Interface

by DAVID R. MILLER, *assistant professor of Natural Resources, Natural Resources Conservation Department, The University of Connecticut, Storrs, Conn. 06268.* *This research was supported by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry studies.*

ABSTRACT.—Radiation balances and vertical and horizontal profiles of air temperature, vapor pressure and wind speed were measured across the interface of a large asphalt parking lot and an 18-m-tall *Quercus velutina* forest. The partitioning of available energy over the adjacent areas shows steep gradients between the parking lot and forest microclimates. Horizontal temperature and humidity gradients across the interface were on the same order of magnitude as the vertical gradients above the respective surfaces.

URBAN ENCROACHMENT into forested areas is one of the major land-use changes occurring in the eastern coastal region of the U.S. This transfer of forest land to urban uses takes place with little knowledge of or thought given to the maintenance of the forest as a naturally occurring environmental buffering system. It is possible, however, that methods can be devised to successfully mesh urban expansion into the forest environment while maintaining the ability of the forest to ameliorate the suburban climate.

This study was devised to quantify the physical exchanges of air-transported latent heat (water vapor) and sensible heat between and within forested areas and adjacent paved areas. Knowledge of the magnitude and variations of these exchanges can lead to the determination of the microclimatic impact of developments in wooded areas. It also may allow the size, orientation, and composition of proposed city plantings and greenbelts to be designed to maximize any ameliorating effect on the local city microclimates.

ENERGY BUDGETS

The radiant energy absorbed at the earth's surface (Rn) is dissipated by evaporating water (LE), heating the air (A), and heating materials on and below the surfaces (S).

$$Rn = LE + A + S \qquad [1]$$

There are other processes that may affect the surface energy balance, which are not included in equation 1, such as photosynthesis, respiration, and canopy storage of energy. These are very small consumers of energy and can be neglected in this case.

In a given localized urban environment with no vegetation, there is no large source of water for evaporation. Therefore, the available radiant energy is used primarily to heat the air and the various materials that make up the surfaces in the city.

$$Rn = A + S \qquad [2]$$

Buildings and paving, having large heat capacities, absorb large amounts of heat during the day, making S a much larger term than in a natural environment. Convection processes convert much of this to sensible heat immediately during the day and later into the night.

In adjacent vegetated areas the relative amounts of energy utilized in LE and A vary as a function of the type of vegetation, the soil moisture available for transpiration, and the potential evapotranspiration rate.

The ratio of the fluxes of sensible heat and latent heat (A/LE) or Bowen Ratio

$$\beta = A/LE \qquad [3]$$

can be estimated from the temperature and humidity gradients above the canopy:

$$\beta = \frac{Cp\,\rho\,Ka\,\frac{\partial T}{\partial z}}{\frac{Mw/Ma}{P} L\,Ke\,\frac{\partial e}{\partial z}} \qquad [4]$$

where:
- Cp = the specific heat of air
- ρ = the air density
- Ka = the turbulent exchange coefficient for sensible heat
- T = the air temperature
- Mw/Ma = the ratio of the molecular weights of water and air
- P = the atmospheric pressure
- L = the latent heat of vaporization
- e = the vapor pressure of water in air
- Ke = the turbulent exchange coefficient for water vapor
- z = height

If the ratio Ka/Ke is known, or the equality of Ka and Ke is assumed, then equation 4 can be solved with measurements of the gradients of temperature and air vapor pressure. The Bowen Ratio thus determined can then be used with the energy balance, equation 1, to determine the fluxes of LE and A:

$$LE = \frac{Rn - S}{1+\beta} \qquad [5]$$

$$A = \frac{Rn - S}{1+\frac{1}{\beta}} \qquad [6]$$

The usefulness of the one-dimensional Bowen Ratio model is in question near a surface discontinuity. It is valid only when the vertical fluxes of LE and A are independent of height (z) above the canopy. Therefore, it can be used only when measurements are made within the internal boundary layer, which forms at the windward (leading) edge of a stand and thickens with distance downwind.

Little information on the boundary-layer thickness above very rough surfaces such as forests is available. Shinn *(1971)* calculated, from wind-tunnel shear-stress measurements above a simulated forest canopy (see *Sadeh 1974* for measurement details), that the thickness of this boundary layer (a) grew linearly with horizontal distance (x) for at least 25 canopy heights (H) from the leading edge.

$$\Delta a = 0.08x, \qquad x \leq 25H \qquad [7]$$

METHODS

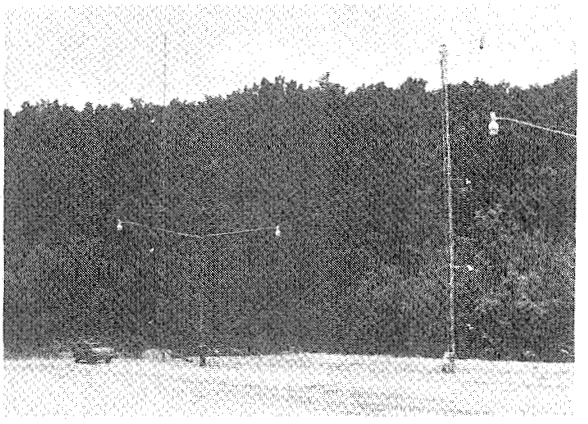
Three towers were installed across the interface of a 1.8-ha asphalt parking lot and an adjacent black oak *(Quercus velutina)* forest in Storrs, Connecticut, Lat. 41°47′30″N, Long. 72°14′30″W. Wind speeds, air temperature, and humidity were measured with sensitive cup anemometers and aspirated thermocouple psychrometers at four heights on each tower, extending above the canopy of the forest.

The forest was 20 m tall. One tower was located at the edge, one approximately 2H (H = tree height) within the forest, and one approximately 2H out into the parking lot (fig. 1).

Net radiation (Rn), ground heat flux (S), and ground surface temperatures were measured in both the parking lot and the forest with miniature net radiometers, heat flux disks, and thermocouples respectively. The instrumentation and data recording system used are described in Miller et al. *(1975)*. Data were collected during the summers of 1973 and 1974 under a number of different synoptic weather conditions.

Smoke tracers were utilized to observe the three-dimensional patterns of air movements under various synoptic conditions. Smoke was released at several

Figure 1.—Parking lot and edge towers and the experimental site forest vegetation of predominately black oak (*Quercus velutina*).



heights at the edge and at varying distances from the edge.

RESULTS

The Energy Balances

Figures 2 and 3 show the partitioning of the energy balances over the two areas on a sample day, 4 July 1974. Flux of sensible heat (A) in the parking lot was calculated from equation 2. A and LE over the forest were calculated from equations 5 and 6 from gradients measured within the boundary layer as defined by equation 7.

The net radiant energy available (Rn) over the parking lot and forest were within 2 percent of each other. The soil heat flux (S) was approximately 20 percent of Rn in the parking lot and 2 percent of Rn in the forest.

Most of the available energy above the forest (f) was used to evaporate water ($LE_f \approx .8$ Rn), while in the parking lot ($_P$) most of the available energy was sed to heat the air ($A_P \approx .8$ Rn).

Air Temperatures and Humidities

The air temperature over the parking lot warmed faster after sunrise and cooled faster after sunset than in or over the forest. After sundown the parking-lot air was cooler through much of the

Figure 2.—The parking lot energy budget, air temperature, surface temperature, and air vapor pressure, July 4, 1974.

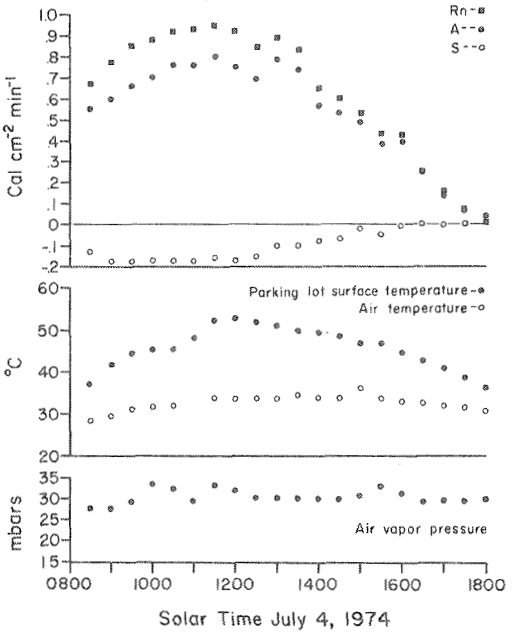
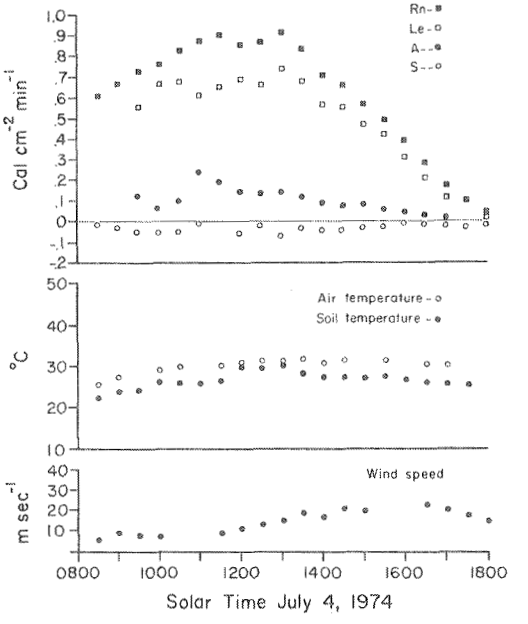


Figure 3.—The forest energy budget, air temperature, soil temperature, and windspeed (above the canopy), July 4, 1974.



night than the air under the forest canopy. This differential cooling and warming was in response to parking-lot surface temperatures, which ranged up to 55°C on some clear days. The daytime horizontal air temperature differences between the parking lot and forest were on the order of 3°C on warm days.

Air above the top of the canopy was heated most rapidly during the day and cooled at night similar to, although slower than air above the parking-lot surface. Therefore the profiles above the canopy were similar to but less steep than those above the parking lot.

The edge temperatures were similar in magnitude to those in the parking lot during the day, with slightly delayed heating and cooling responses. At night the edge temperatures were closer to those in the forest.

Vapor pressure data showed the forest to be consistently more humid than the parking lot. Near the ground the horizontal differences between the forest and open were generally on the order of 2 to 3 millibars both day and night.

Figure 4 demonstrates midday temperature and vapor pressure gradients across the edge on a clear day with the wind blowing into the stand *(Miller 1975)*.

Effects of Wind Direction

The data shown in figures 2, 3, and 4 are from periods when the wind was blowing into the stand.

Figure 4 shows steep horizontal gradients of VP just outside the forest edge and temperature gradients well into the forest. When the wind was from the forest, the horizontal temperature difference was smaller. The water vapor was apparently transported well out into the parking lot.

Figure 5 shows the forest energy balance on 6 July, a day with the wind from the forest. The ratio of A to LE above the forest on 4 July (wind into the stand) was slightly smaller than 6 July (wind from the stand). But no consistent trend in this effect could be correlated. Therefore the differences in ratio on these two days were ascribed to the higher potential evapotranspiration rates on 4 July.

Figure 4.—Air temperature isotherms (solid lines) and air vapor pressure isobars (dotted lines) across the parking lot forest edge with the wind blowing into the forest (after *Miller 1975*).

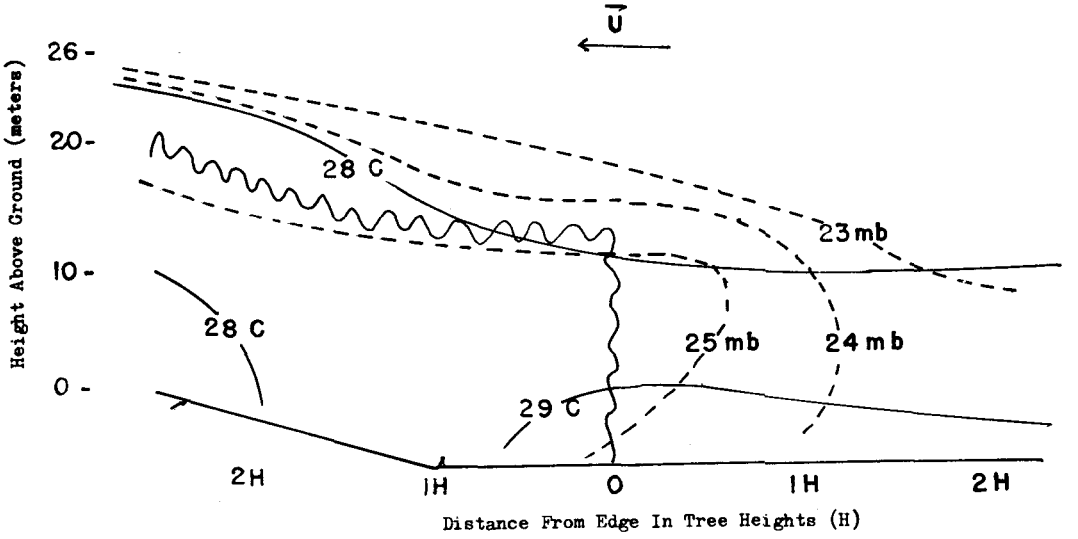
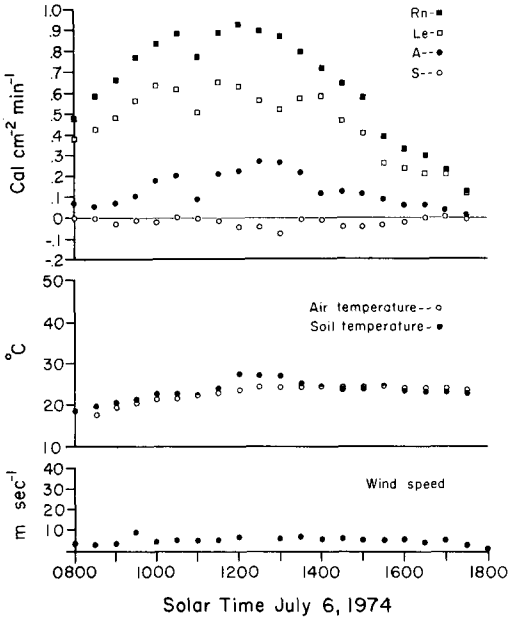


Figure 5.—The forest energy budget, air temperature, soil temperature, and windspeed (above the canopy), July 6, 1974.



Advection Across the Interface

The term advection is used here to mean horizontal transport of an air property such as sensible or latent heat.

Smoke releases showed that the air from the parking lot penetrated the forest edge easily and steadily when the wind direction was from the open to the forest. An occasional weak vortex appeared at the edge during periods of very low wind speeds. Once the smoke penetrated the stand edge it drifted and dissipated below the temperature inversion at the top of the canopy.

Calculations of the amount of sensible heat transported across the interface were presented by Miller *(1975)*. From the horizontal temperature and wind speed gradients it was estimated that between 10 and 20 percent of the sensible heat produced on the parking lot was advected into the adjacent tree stand.

DISCUSSION

The profile data suggest that the region of the interface can be broken into three distinct microclimates. One is formed over the forest, and its characteristics are determined primarily by the energy exchanges at the top of the canopy. The second is formed beneath the canopy. The third is formed over the parking lot and is characteristic of the exchanges at that surface.

The characteristics of the interfaces or mixing boundary layers between the three air masses change both spatially and over time as each of the microclimates responds to changing conditions. Apparently the interface between the parking lot air and that beneath the canopy moved horizontally and was within the forest edge during the day and outside it at night. This indicates that when sensible heat moved horizontally, from the forest at night and to the forest during the day, the major portion of the air mixing takes place some distance beyond the edge in the direction of movement.

These findings combined with those of Bergen *(1975)* indicate that the edge effects extend about 2 to 3 tree heights into the forest. Here the horizontal temperature gradients and wind velocities decreased rapidly inside the forest. At the tower site approximately 2H into the forest, the temperature gradients and wind speeds were very weak, indicating little if any advection that far into the forest. The effects of the edge on the air turbulance were indicated by Bergen *(1975)*, who calculated increased drag on the air mass some 30 meters (approximately 3H) downwind of a clearing in the forest.

The extent of the edge effects into the parking lot are a little less clear. The smoke tracers showed that with wind from the lot, air from greater than 2H penetrated the edge when the windspeed was greater than 4 mph. When less than 4 mph only the smoke released near the edge penetrated. When the wind was

from the forest there were changes in the temperature and vapor pressure gradients well beyond the location of the tower located 2H into the parking lot *(Miller 1975)*.

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Outdoor Comfort of Pedestrians in Cities

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ABSTRACT.—The outdoor comfort of pedestrians has been neglected by architects and planners because of difficulties in determining comfortable and uncomfortable climatic conditions and predicting the climatic characteristics of a planned urban site. Available information on comfort in a cold environment is summarized. The mechanical effects of wind on comfort are better understood than the thermal effects of climate and have proved to be practical criteria for assessing pedestrian comfort in designs. Climatic-prediction techniques and a procedure for determining the probability of discomfort on a proposed site are described.

HUMAN COMFORT is determined by many factors, both psychological and physiological. Some of these factors, such as acoustics and indoor climate, have an extensive history of quantification and control. The existence of standards for these variables requires that they be considered in design.

Other factors, such as outdoor visual effects (light, surface, forms) and spatial relations (enclosure, security), though not quantified or standardized, are of concern to the architect and are intuitively incorporated in design.

The effect of outdoor climate on comfort, however, is often ignored by the architect or planner. It has been neglected to date because of difficulties in (1) determining what climatic conditions are comfortable or uncomfortable, and (2) predicting the climatic characteristics of a planned site.

In this paper, available information about discomfort due to wind effects is summarized and tentative design criteria are presented. A model describing pedestrian cooling in a cold climate is also given, and its shortcomings in defining design criteria are described. Design criteria from these two methods are applied to an urban site, using climatic data and data from wind- tunnel and sun-shadow tests on a scale model. A procedure for designing for outdoor comfort by controlling wind and sun (the most important and most easily varied factors) is presented.

INFLUENCES OF CLIMATE ON COMFORT

Mechanical Influences of Wind

Wind influences comfort through pressure effects and particle transport. Wind pressure affects comfort through disturbance of clothing and hair, resistance to walking, and buffeting of the body and carried objects like umbrellas. Comfort is also affected when the wind lifts dust and grit particles to eye level, or drives rain horizontally into the eyes or beneath clothing. At higher speeds, wind can also interfere with walking and cause safety problems.

These different effects begin at different wind speeds. Their threshold velocities suggest the onset of various types of discomfort and perhaps the basis for some wind-comfort criteria.

A summary of wind effects in terms of the well-known Beaufort scale (table 1) is taken from a land-effects version

prepared by the British Meteorological Office, with additions by Penwarden *(1973)*. Most of the included effects have been observed by ourselves and others in the natural wind and in wind-tunnel experiments *(Arens 1972)*.

Although the Beaufort scale is commonly used to describe velocities averaged over perhaps an hour, our observations show that the wind effects listed for each Beaufort category correspond more closely to the wind velocities observed as they happened. The averaging time might be on the order of, say, a minute and includes the effects of small-scale gusts and lulls but not large ones. Therefore an hourly averaged wind in one Beaufort category will probably include gusts that cause effects ascribed to higher Beaufort categories.

Wind pressures in steady winds

The wind pressure on the human body and the angle of lean needed to counteract it are summarized in the equation *(after Penwarden 1973)*:

$$\tfrac{1}{2}\,\rho\,u^2\,A_P\,C_D/W = \tan\theta/\cos\theta$$

in which θ is the angle of lean from the vertical to counteract wind.

$$\tan\theta = \frac{\text{wind force}}{\text{body weight}}\,.$$

W is body weight.

$\tfrac{1}{2}\,\rho\,u^2\,A_P\,C_D$ equals wind force.

ρ is the density of air.

u is wind speed.

A_P is projected surface area normal to wind, found to be 0.3 total body surface area for frontal winds *(Pugh 1971)*.

C_D is a dimensionless drag coefficient, experimentally determined to be between 1.0 and 1.3 *(Pugh 1971)*.

$\cos\theta$ is a term reflecting reduction of A_P with lean.

Total body surface area (A_{Du}) is obtained from body height and weight by DuBois formula:

$$A_{Du} = 0.203\ W^{0.425} \cdot h^{0.725}$$

in which W is in kilogram force (kgf) and h is in meters.

Assuming a man of 75 kgf, 1.8 meters height, total DuBois surface area of 1.93 m^2, and drag area of 0.84 m^2, the relation between wind speed, drag force, and angle of lean can be calculated (fig. 1).

Energy required to walk against a steady wind

The rate of performing external work is the product of the wind force and walking speed:

$$\text{Work rate} = \tfrac{1}{2}\,\rho\,(u+V)^2\,A_P\,C_D\,V$$

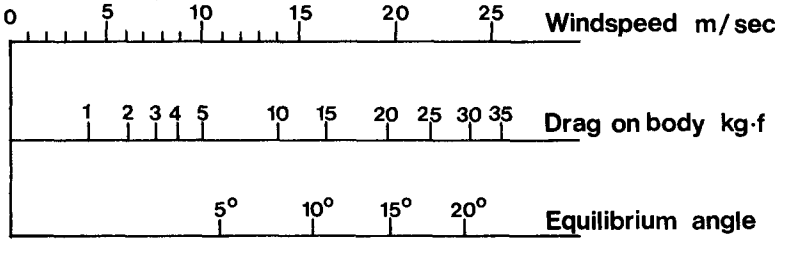
in which V is the velocity of walking into the wind.

The total increase in metabolic rate of the body M resulting from the work of walking into the wind is

$$\Delta M = \tfrac{1}{2}\,\rho\,(u+V)^2\,A_P\,C_D V/\eta$$

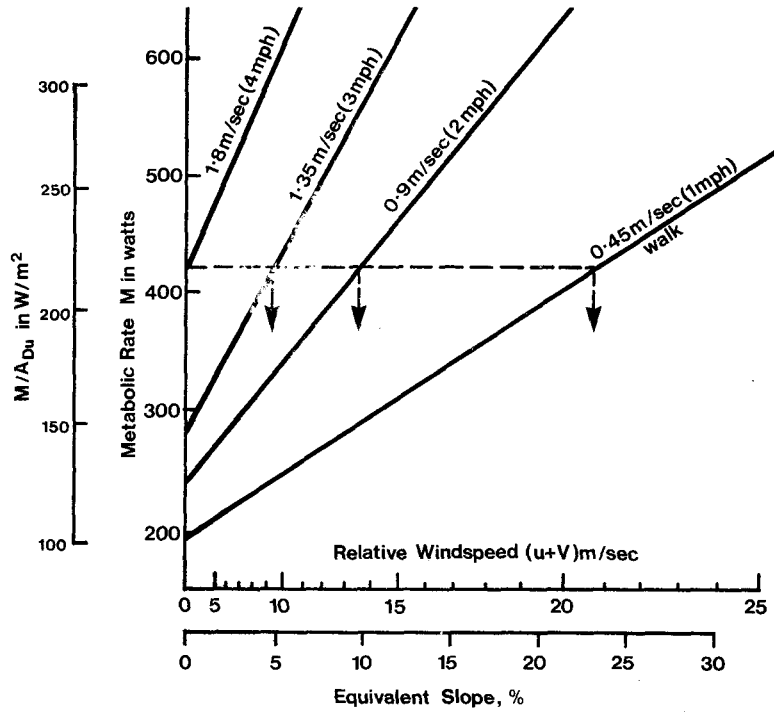
in which η = mechanical efficiency, or (work rate) / (metabolic rate), which Pugh *(1971)* found to be 0.44 for walk-

Figure 1.—Wind forces and equilibrium angles.



Adapted from A D Penwarden 1973

Figure 2.—Work rates of walking against the wind *(Penwarden 1973)*.



ing against the wind and 0.33 for climbing hills. Penwarden *(1973)* presented these data in a diagram (fig. 2) in which the metabolic rates required for walking into the wind are compared to those for walking uphill. The metabolic rates are expressed in watts and in watts/m^2 for the man mentioned above. Penwarden *(1973)* suggests that, if the upper metabolic rate limit for average unathletic people is taken as 220 watts/m^2 (equivalent to walking 4 mph in still air), walking speed into the wind is reduced as follows:

Wind speed	*Walking speed*	
(m/sec)	*(m/sec)*	*(mph)*
0	1.8	4
9	1.35	3
14	.9	2
21	.45	1

These values may be compared to the subjective estimates in the Beaufort scale (table 1).

Effects of turbulent winds

Wind at the pedestrian level is accompanied by turbulence, which is perceived as a varying velocity, as gusts, or as eddies. The intensity of turbulence for any given windspeed varies from place to place but tends to be greater in urban or built-up surroundings than in open countryside.

To learn the effect of most natural winds on comfort, it is necessary to quantify the influence of the turbulent component of that wind. This information has not been available until very recently.

In an exemplary study, Hunt and others tested subjects in both steady and turbulent winds in a wind tunnel *(Hunt et al. 1976, Poulton et al. 1975)*. They also tested the effects of wind variation over a short distance, such as when one walks out of a doorway into the wind. They assessed wind influence on comfort, disarrangement of clothing and

Table 1.—Summary of wind effects

Beaufort number	Description	Wind[1] (m/sec)	Effects
0	Calm	0	Calm
1	Light air	0-1	No noticeable wind; direction shown by smoke.
2	Light breeze	2-3	Wind felt on face; newspaper reading becomes difficult.[2]
3	Gentle breeze	4-5	Wind extends light flag; hair is disturbed; clothing flaps.
4	Moderate breeze	6-7	Dust, dry soil, and paper raised; rain and sleet driven;[2] hair disarranged.
5	Fresh breeze	8-10	Force of wind felt on body; drifting snow becomes airborne; limit of agreeable wind on land.
6	Strong breeze	11-13	Umbrellas hard to use; difficulty walking and standing; wind noise in ears unpleasant; windborne snow above head height (blizzard).
7	Near gale	14-16	Strong inconvenience felt when walking.
8	Gale	17-20	Generally impedes progress; great difficulty with balance in gusts.
9	Strong gale	21-24	People blown over by gusts; slight structural damage occurs; slate blown from roofs.
10	Storm	25-28	Seldom experienced on land: trees broken or uprooted; considerable structural damage occurs.

[1] Rounded from knots in the original scale. (1 m/sec=1 meter per second =1.94 knots=2.2 miles per hour).
[2] Our observation.

Table 2.—Summary of wind-pressure effects on people

[Symbol < denotes 'should be less than']

Wind and effect	Criterion
Steady uniform wind:	
For comfort and little effect on performance	$u <$ 6 m/sec
For ease of walking	$u <$ 13-15 m/sec
For safety of walking	$u <$ 20-30 m/sec
Non-uniform winds (if u varies by 70% over a distance less than 2 m):	
To avoid momentary loss of balance and to be able to walk straight	$u <$ 9 m/sec
For safety (for elderly people this criterion may be too high)	$u <$ 13-20 m/sec
Gusty winds:	
For comfort and little effect on performance	$u_s <$ 6 m/sec*
Most performance unaffected	$u_s <$ 9 m/sec
Control of walking	$u_s <$ 15 m/sec
Safety of walking	$u_s <$ 20 m/sec

*Note: u_s is not the "peak gust" as used in engineering.
Source: Hunt and others (1976).

hair, eye watering, performance of tasks, and balance while standing and walking. Quantification was based on subjective verbal assesments by the subjects and on physical measurement of task performance and of wind forces while walking as transferred to an instrumented floor.

These findings show people to be very sensitive to turbulence in the wind. To compare turbulence effects to other wind effects, an equivalent steady wind is defined:

$$u_s = u\ (1 + 3 \cdot \text{turbulence intensity})$$

in which

u_s = Equivalent steady-wind velocity.
u = Mean velocity.
turbulence intensity = (root mean square of the instantaneous

deviations from the mean velocity)/u

The limiting velocities have been summarized (table 2).

Wind-driven rain and particles

A pedestrian may also be inconvenienced by rain or grit blown into his face. Blowing grit may well be the most unpleasant single effect of the climate on a pedestrian.

The suspension of a solid or liquid particle requires an upward air velocity equal to the terminal velocity of the particle (table 3). A horizontal wind equal to or exceeding the terminal velocity will cause a particle to descend at an angle of 45° or less to the horizontal.

It can be seen that a horizontal wind speed of 7 m/sec will cause large raindrops to descend at 45°. This value is used by building climatologists for driven-rain data; however, fine drizzle will be driven at 45° by velocities as low as 1 m/sec.

The size of droplet and angle of fall that individually and in combination are considered unpleasant are unknown. It is probable that flatter angles of descent are acceptable for smaller droplet sizes, since wetting by rain takes time. This might allow us to define a single limiting velocity for rain. We do not have information at present, but it will be between 1 and 7 m/sec.

Wind-lifted dust has a major impact on human comfort. In the Beaufort scale, dust and loose papers are described as being lifted at velocities between 5.5 and 8 m/sec.

A physical formulation of this process depends on a number of unresolved factors such as the minimum particle size needed to cause irritation in the eye and on the skin, the mechanisms of particle lifting from urban paved surfaces, and the extent to which moisture cements particles together.

The lifting mechanism is described by Bagnold *(1941)* and Chepil *(1965)* in relation to desert sand and soil particles, respectively. Bagnold shows that particles begin rolling at around one-seventh the velocity needed to lift them. This suggests that grit traps (lawns, gratings, and water) might be useful in reducing the supply at the surface.

Lifting requires vertical velocities that are inherent in a boundary layer over a surface or that are caused by obstructions protruding from the surface. When the eddies are caused by surface friction, Bagnold shows that a horizontal velocity at 1.5 meters of 8 to 14 m/sec will lift 0.1-mm grit from flat surfaces.

Near wind-deflecting vertical obstructions, the vertical velocities close to the ground for a given mean wind speed are much higher. These vertical velocities may be in the form of vortices in fixed locations relative to the obstruction. Examples are eddies behind lamp posts, near building corners, or in streets near moving vehicles. Although these local eddies may lift dust and paper when the winds are light, they are often not perceived because the dust supply in their immediate area is exhausted.

Wind between 5 and 8 m/sec will probably cause pedestrian discomfort by blowing dust, paper, or rain.

Table 3.—Terminal velocities of airborne particles

Velocity	Diameter of particles	Character of particles
m/sec	*mm*	
10^{-2}	0.01	Dust
10^{-1}	.03	Extremely fine sand, dry snow
0.6	.1	Fine sand
1	.2	Medium sand, snow, sleet, fine rain
2.5	.3	Average sand in the desert
7	1.0	Large raindrops*
10	1.0+	Sand to pebbles, great rain, hail

Sources: Bagnold *(1941)*, Reidat *(1970)*.*

Design criteria: mechanical wind effects

The British Building Research Establishment recommended 5 m/sec as the design wind velocity under urban outdoor conditions *(Wise 1970)*. As de-

scribed above, recent results by Hunt et al. define this design value more closely in terms of the steady and turbulent components.

With a design value in hand, the designer must judge what percentage of the time (or how often in a year or season) it may be exceeded. For comfort, 10 to 20 percent may seem reasonable. For safety, lower exceedance percentages (say 1 percent) should be applied to the higher design values. Davenport *(1972)* has suggested acceptable exceedance frequencies for a variety of activities based on a 5 m/sec design windspeed; the reasons for the suggested frequencies are not given.

Penwarden *(1974)* analyzed cases of shopping centers that had caused wind complaints. He found that in centers where 5 m/sec was exceeded 20 percent of the time or more, the owners invariably spent the money to add protective screens or roofs. Centers with frequencies of 10 to 20 percent caused complaints but no remedial action, and few complaints were heard in centers with frequencies below 10 percent. Penwarden's study gives the most concrete evidence in support of specific design criteria to date.

THERMAL INFLUENCES OF CLIMATE ON COMFORT

A person's thermal comfort is influenced by the surrounding air temperature, wind, radiation, and humidity, as well as his clothing insulation and activity level. Thermal comfort has been studied extensively for indoor conditions (see *Fanger 1970*).

Because of the increased range of climatic variables outdoors, investigators have not been able to quantify the perception of thermal comfort versus climate in outdoor environments. See Penwarden *(1973)* for a summary of such work.

Most attempts to define the effects of climate on people have used thermal budget models in which it is assumed that comfort results from the thermal balance between the body's heat production and heat losses to the environment. These models assume equilibrium heat flow, which in reality occurs only after 1 to 2 hours' exposure to constant surroundings. The physical and psychological response of people to changing thermal environments has been studied only for nude subjects in indoor laboratory conditions *(Gagge et al. 1967)*.

Model for heat loss to a cold outdoor environment

The following describes a model of thermal comfort used to assess the environmental quality of buildings in the cool San Francisco environment. Total heat loss from the body is the sum of dry heat loss (convective, radiative, and conductive) and insensible evaporation from skin and lungs. Evaporation is roughly independent of atmospheric humidity and represents a roughly constant 25 percent of the body's heat loss. It has not been possible to demonstrate any difference between the popular "wet cold" and "dry cold." Conductive losses are low in pedestrians and are ignored. The dry heat loss is thus defined as:

$$kQ = \frac{A_c}{A_{Du}} \left(\frac{T_b - T_a}{R_b + R_c + R_a} \right) + \frac{A_n}{A_{Du}} \left(\frac{T_b - T_a}{R_b + R_a} \right)$$

in which:

Q is total heat loss from body.

k is the fraction of non-evaporative heat loss (0.75).

A_c and A_n are the surface areas of clothing and exposed nude skin, respectively.

A_{Du} is the DuBois total nude surface area (see previous definition in section on "Wind pressures in steady winds.")

T_b is body core temperature, normally 37° C.

T_a is mean radiant temperature, the av-

erage temperature of air and radiant surroundings.

R_b is the insulation of body tissues commonly assessed as 0.09 m^2 deg C/watt.

R_c is insulation of clothing itself.

$$R_a = \frac{1}{h_r + h_c} = \frac{1}{4.3 + 12u^{0.5}}$$

where h_r and h_c are the radiative and convective heat transfer coefficients; h_c has a minimum value of 4 watts/m^2 °C in still air.

Insulation of clothing is commonly given in "clo" units, equal to 0.155 m^2-°C/watt. Clothing insulation is usually quantified by measuring the power consumption of a dressed heated mannikin in still air and describing the resulting insulation as uniformly distributed over the entire body surface. Because this method does not allow for the disproportionate influence of wind on nude as opposed to clothed surfaces, the above formula treats the two surfaces as parallel heat losses. The value of R_c must be selected to represent the garments themselves. For example, 1 clo traditionally represents the insulation of a business suit distributed over the entire body, whereas the insulation over the clothed area itself is 1.2 clo.

Solar energy absorbed by the body counteracts heat loss. The incoming radiation's effectiveness in heating the body is proportional to the amounts of insulation within and without the point of absorption; i.e., solar heat gain Q_I is greater for nude than clothed surfaces:

$$\text{For nude, } Q_I = \frac{R_a}{R_b + R_a} I\,(1 - a)$$

$$\text{For clothed, } Q_I = \frac{R_a}{R_b + R_c + R_a} I\,(1 - a)$$

where I (1 - a) = Absorbed solar radiation at the surface.

I = Total solar influx on the body surface, watts/m^2.

a = Reflectivity of clothing or skin, ranging from 0.8 for white clothing, 0.43 for white skin, to 0.16 for black clothes or skin.

If we let I(1-a) = S, then the net dry heat loss equals

$$kQ - Q_I = \frac{A_c}{A_{Du}} \left(\frac{T_b - T_a - SR_a}{R_b + R_c + R_a} \right) + \frac{A_n}{A_{Du}} \left(\frac{T_b - T_a - SR_a}{R_b + R_a} \right)$$

Solar radiation influx includes direct beam, diffuse sky, and reflected components. The proportions of the total body surface A_{Du} exposed to these streams have been calculated and measured *(Blum 1945)*. Body surface area exposed normally to the direct beam varies from 7 percent A_{Du} to 30 percent A_{Du} as the sun moves from the zenith to the horizon. In practice, the increased area exposed to low-altitude sun nearly compensates for the decreased intensity of the direct beam. One-half of A_{Du} is assumed to be exposed to the diffuse radiation from the sky vault and the other half to the radiation reflected from the ground. These exposure proportions of the total body surface are assumed to apply to the clothing and exposed skin surfaces as well. The sky and ground may be assumed to radiate at uniform intensities for the purposes of this model.

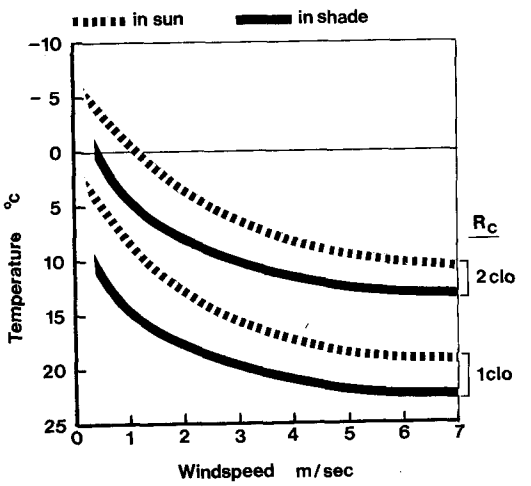
An equivalent treatment can be applied to longwave radiation gain or loss when the temperatures of surrounding surfaces are substantially different from air temperature. In these cases air temperatures would represent the surroundings and a is 0.05. The differences between the air and outdoor surface temperatures are usually too small to warrant this refinement.

Thermal balance exists when the net heat loss (Q-Q_I) is equal to the metabolic heat production M (table 4). "Comfort curves" (fig. 3) can be drawn for heat loss versus wind and temperature for various sun and clothing levels.

Table 4.—Metabolic rates

Activity	Metabolic rate M/A_{Du}
	Watts/m²
Sleeping and digesting	47
Sitting quietly	59
Standing	71
Strolling—0.7 m/sec (1.5 mph)	107
Level walking—0.9 m/sec (2 mph)	116
Level walking—1.35 m/sec (3 mph)	150
Level walking—1.8 m/sec (4 mph)	220
Level walking—4.5 m/sec (10 mph)	590
Sprinting—10 m/sec (22 mph)	2,400

Figure 3.—Sample comfort curves for a range of temperature and windspeed. $M/A_{Du}=150$ watts/m², equivalent to walking 3 mph. Direct sun on horizontal surface=285 watts/m².



These have the following shortcomings:

1. They assume thermal equilibrium, which requires 1 to 2 hours' continuous exposure to the outside environment. This is rare for pedestrians.
2. They show no effect of wind penetration or infiltration of clothing. There is a serious lack of experimental data on clothing performance in wind.
3. Clothing resistance is not easily defined for any civilian population, due to the extreme variability of clothing worn at any time. The curves are sensitive to the chosen value of R_c.
4. There is virtually no experimental evidence describing how physiological heat loss influences the psychological perception of comfort outdoors.

DESIGN PROCESS

The designer should consider outdoor comfort early in his design. Because the relationship between the physical form of the design and the climate and comfort around it is often complex, he may have to follow a climatic design process in order to find a satisfactory solution. The process is basically to: (A) determine the climatic characteristics of the site and the preliminary project, partly by model tests; (B) assess its effects on outdoor comfort; and (C) modify the project design and test the climate and comfort again until a solution is reached.

PREDICTING THE LOCAL CLIMATE OF A SITE

Solar radiation and wind are the most important climate information for comfort prediction. Of the various climatic elements, these have the greatest variation across a site of architectural or planning scale. They are also the climatic elements over which the designer has most control. Elements with less site variations and importance to comfort analysis are longwave radiation, air temperature, and air humidity.

Solar Radiation

The important facts about sunlight are its duration and its intensity. These are influenced by both the geometrical and meteorological nature of the site and its location.

Regional scale. — Daily possible solar duration is readily available in standard meteorological tables and is a geometric function of latitude. Solar duration is further influenced by the meteorological probability of sunlight or cloud. These data are readily available from the Weather Service as seasonal or hourly values of percent cloudiness, percent of possible sunshine, or number of hours of cloud.

Solar intensity is influenced by lati-

tude (atmospheric path length) and atmospheric turbidity. Solar intensity is not widely measured and, if available, is usually in the form of daily total energy per unit area.

A most useful method of obtaining average hourly solar intensities is given by Liu and Jordan *(1960)*, based on observed constancy between daily and hourly values in regions of equal atmospheric clarity.

Local Scale. — On the site itself, solar radiation is described by its extent and by the amount of time it is either on or off. The surrounding buildings either obstruct or admit light to the pedestrian areas. There is little variation in the intensity of direct sunlight in most outdoor spaces. Local exceptions might occur in places screened by thin vegetative canopies or near highly reflective surfaces.

Sunlit and shaded areas may be predicted from a model with a light source representing the sun. The daily sunlight characteristics of an existing site are conveniently determined by use of a globoscope or of fisheye photographs of the sky hemisphere overlain with appropriate sunpath diagrams. An excellent description of solar geometry prediction techniques for designers is given by Burberry *(1966)*.

A computer program has been developed at the Department of Architectural Science, University of Edinburgh, to integrate shadow areas over any period of day and present these shadow durations in contour form. We have not used this technique, although it could be useful in the eventual preparation of daily "comfort contours."

Wind

Regional scale. — Wind records are available for most locations; recording stations are commonly found at airports in open terrain. For most sites wind information must be extrapolated geographically from the recording station to the vicinity of the site. The effects of topography, vegetation, and structures must be carefully considered in this extrapolation. If possible, wind-recording equipment installed on site should be run synchronously with nearby weather stations for a suitable period of time to establish the relation between winds at the two locations. This is expensive and time-consuming, however.

The meteorological data base should provide information necessary to determine the amount of time that pedestrians will be uncomfortable on the site. This requires hourly wind data, preferably in conjunction with data on temperature and sun. The most useful wind summary is a cumulative frequency distribution providing the percentage of time that each wind velocity is exceeded for each wind direction. This data format is rarely available and must usually be calculated from the station's raw data.

Local scale. — Winds at pedestrian level will often be strongly affected by the building, planting, and grading configuration of the project. The wind patterns over the pedestrian areas of a site are far more difficult to predict than the presence or absence of sunlight. If a yet-unbuilt project seems likely to be windy, it should be tested in model form in a wind tunnel. This technique is also useful for defining winds on existing sites, since the flow strength, stability, and direction can be controlled during the tests. Physical modeling with limited field verification is most desirable.

Physical modeling requires the use of a specialized wind tunnel that reproduces the boundary-layer conditions above the actual site. Both the velocity and the turbulence intensity profiles should be modeled to scale. The most satisfactory means of achieving this at present is to generate the boundary layer with turbulence generators and long lengths of roughness similar to that of the terrain upstream of the project site.

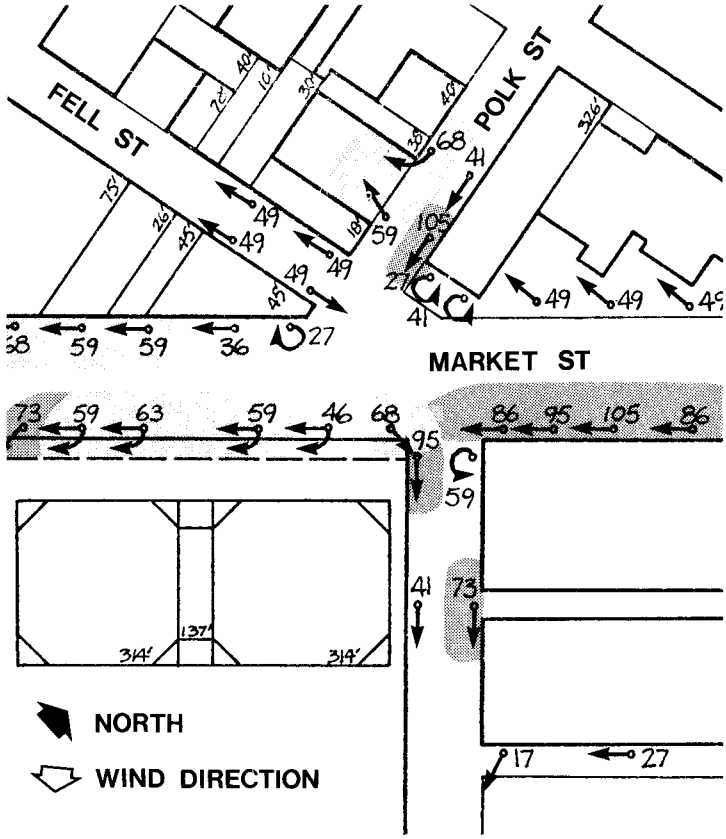


Figure 4.—Nondimensional wind speeds obtained from wind-tunnel tests of a scale model. Shading indicates areas of high wind speeds.

Wind speeds measured in the wind tunnel are nondimensionalized and are expressed as a percentage of a reference wind speed. The reference wind speed is that measured at the reference height, often chosen as the height of the wind instrumentation of the weather station providing climatological wind data. By relating wind-tunnel measurements to climatological data, wind-speed frequency distributions on the site are defined.

Measurements of wind speed are normally made at a network of grid points within and around the project model. A hot-wire anemometer is used to measure wind speed and turbulence at each grid point. Its small size allows it to measure within millimeters of the surface, representing pedestrian height at model scale. Separate tests are made for each wind direction, the number of directions normally corresponding to the number of points of the compass considered in the meteorological wind data base. An example of wind-tunnel data for a downtown San Francisco site is given (fig. 4).

Temperature, Longwave Radiation, Humidity

Air temperature, longwave radiation from the ground and atmosphere, and humidity are important heat-transfer mechanisms; however, they vary little across normal architectural sites.

Temperature. — At a regional scale, one should consider microclimatic effects

when extrapolating a regional air temperature value to the site. Temperature may be substantially modified by frost pockets and urban heat islands, for example. On the site itself the variation is usually much less.

Longwave radiation. — In comfort models, air temperature and the temperature of the surroundings are either assumed equal or averaged into a "mean radiant temperature" that is used as the ambient temperature. Since surface temperatures usually do not differ from air temperatures by more than a few degrees, the difference between longwave radiation contributed by the surfaces on site and that of surroundings at air temperature is very small. In light of the accuracy of the thermal model, calculation of surface temperatures and longwave radiation flux is not justified. In hot environments, where the thermal requirements for comfort are more closely quantified, local surface temperatures and radiation exchange are important design characteristics.

Humidity. — Humidity has no quantified role in cold environment heat loss. In hot environments, humidity plays a critical part in determining comfort.

ASSESSING COMFORT ON A SITE

The complicated interaction of climatic variables that determine comfort can be handled best statistically. A logical and simple measure of comfort is the percentage of time that comfort or discomfort will occur on a given day at a specific time. Care should be taken in selecting the proper season and time for the analysis of comfort so that the period of greatest use or sensitivity to discomfort is considered.

We have used two different criteria defining uncomfortable conditions in our analyses, based first on the thermal and then on the mechanical effects of climate. The computation process for determining discomfort probability is different under these two methods (fig. 5).

Thermal comfort prediction method

For each measurement point, the time of day, day of year, expected type of human activity, and expected level of clothing are specified. The average temperature for this period is then found.

The first step in the calculation involves defining the "discomfort threshold wind speed" from the comfort curves. Separate threshold values are defined for sunny and shady conditions. If the point of interest is shaded by structures or topography, the calculations need only consider the sunless case. If it is in the sunshine, separate calculations must be made for the sunny and shady cases.

The nondimensional wind speeds obtained in the wind tunnel are then used to specify the reference wind speed corresponding to the threshold wind speed on the site for each wind direction; i.e., the threshold wind speed is divided by the nondimensional wind speed.

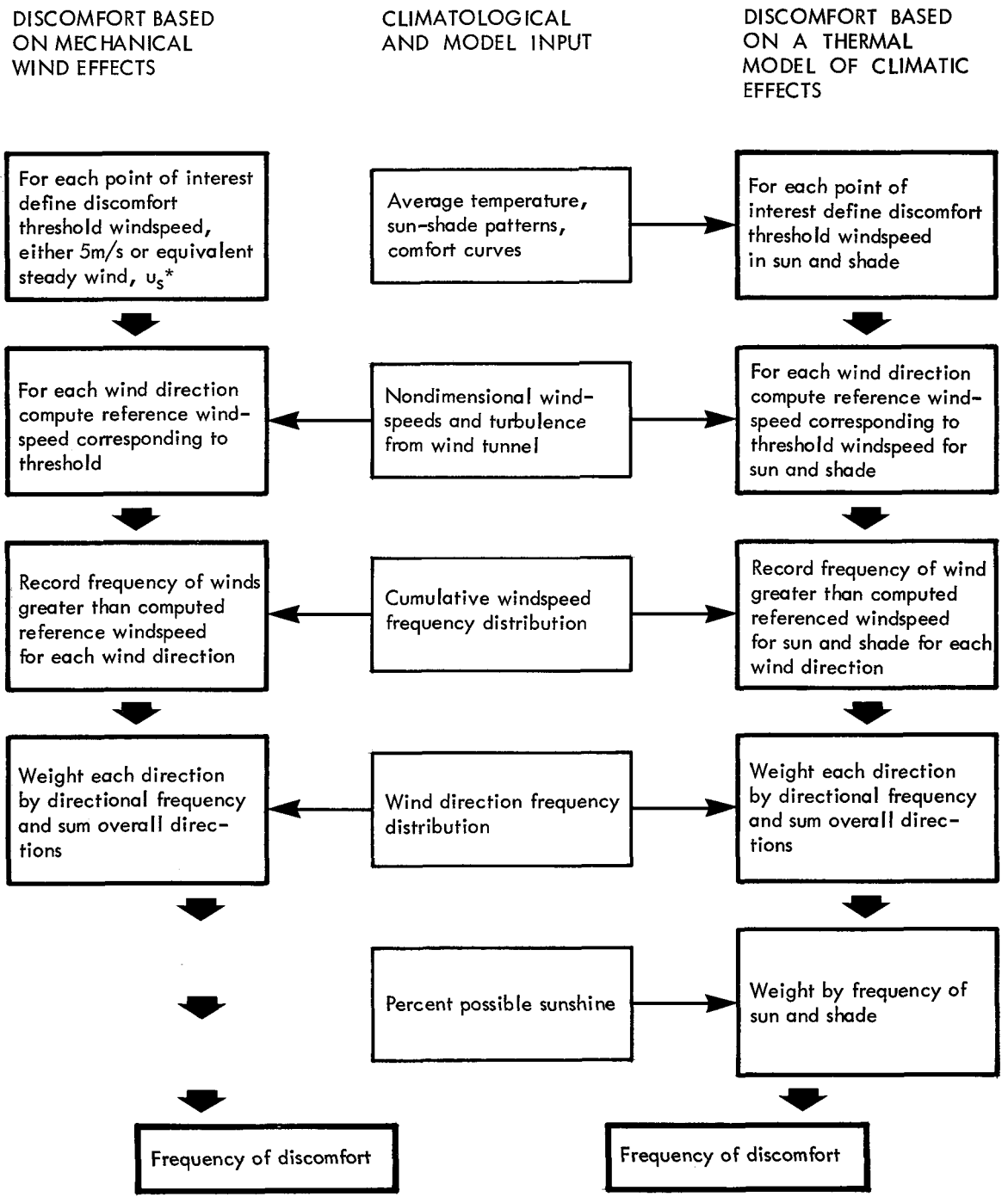
The frequency of reference winds exceeding the specified level is then obtained from cumulative wind-speed frequency curves, again separately for each wind direction and for the sun and shade cases.

The result is the probability of discomfort occurring during wind from each direction. These probabilities are then weighted by the probability of each wind direction's occurrence. For a point in the sun, two separate discomfort probabilities are calculated. They are then weighted by the climatological probabilities of sunshine and clouds and combined into a single probability.

Calculated discomfort frequencies for a downtown San Francisco site are shown as an example (fig. 6). The clothing level chosen is light but corresponds to our estimate of average men's and women's clothing at this time of year.

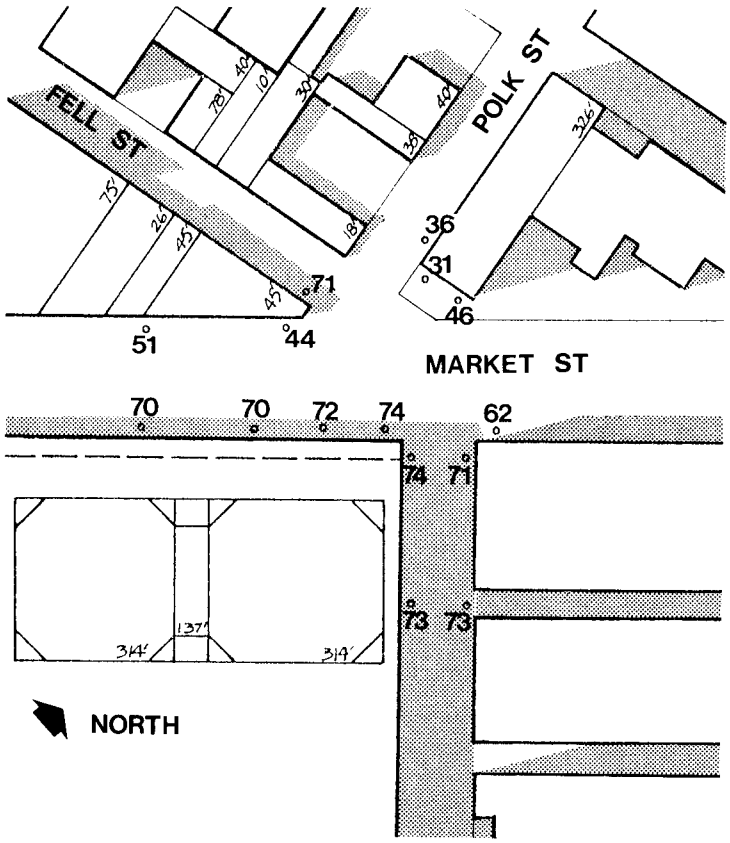
The pattern of discomfort frequency seems reasonable in that shaded areas exhibit a much higher discomfort frequency than areas in the sun. The absolute values, however, are extremely high, especially in the shaded areas. The

Figure 5.—Calculation process in determining discomfort frequency.



*See Table 2

Figure 6.—Frequency of discomfort based on thermal influence of climate. The analysis is for the first day of spring at 1 p.m. with a temperature of 15°C (61°F). The discomfort frequencies are for a person walking 3 miles per hour, wearing clothing with R_C=1 clo, averaged as 0.8 clo over the entire body.



uniformity of the frequencies within the shaded areas is unexpected considering the variation of windspeeds over these areas.

The explanation of these discrepancies lies in the assumptions of the thermal comfort model. As a steady-state model, a period on the order of 1 hour is required for a person to come to thermal equilibrium with the environment. The average duration of a pedestrian trip is more on the order of 5 to 10 minutes, however, so that the steady-state conditions would never be reached.

Applying the steady-state model to a transient situation underestimates the discomfort threshold wind speed. In shady areas the model is so oversensitive to wind that almost any wind will cause discomfort, resulting in discomfort frequencies uniformly approaching the climatological probability of non-calm winds.

While providing poor estimates of comfort in pedestrian areas, the thermal model may be useful in other applications. The assumptions of the model apply to outdoor sports arenas and theaters, picnic areas, and beaches; and the model could provide usable discomfort estimates for such areas.

Comfort prediction method based on mechanical wind effects

The inaccuracies of the steady-state thermal model are avoided by basing comfort prediction on mechanical effects of the wind alone. The computational requirements of this method are also far less. The mechanical method will, of course, underestimate the discomfort frequency by neglecting discomfort caused by thermal cooling.

In the computation (fig. 5) the discomfort threshold speed is now set at 5 meters/second (11 miles per hour), regardless of temperature or sunshine. If turbulence is considered, the equivalent steady windspeed u_s is calculated for each point of interest and used as the discomfort criterion (table 2). The remaining steps are similar to those in the thermal prediction method, except that sun-shade effects are ignored.

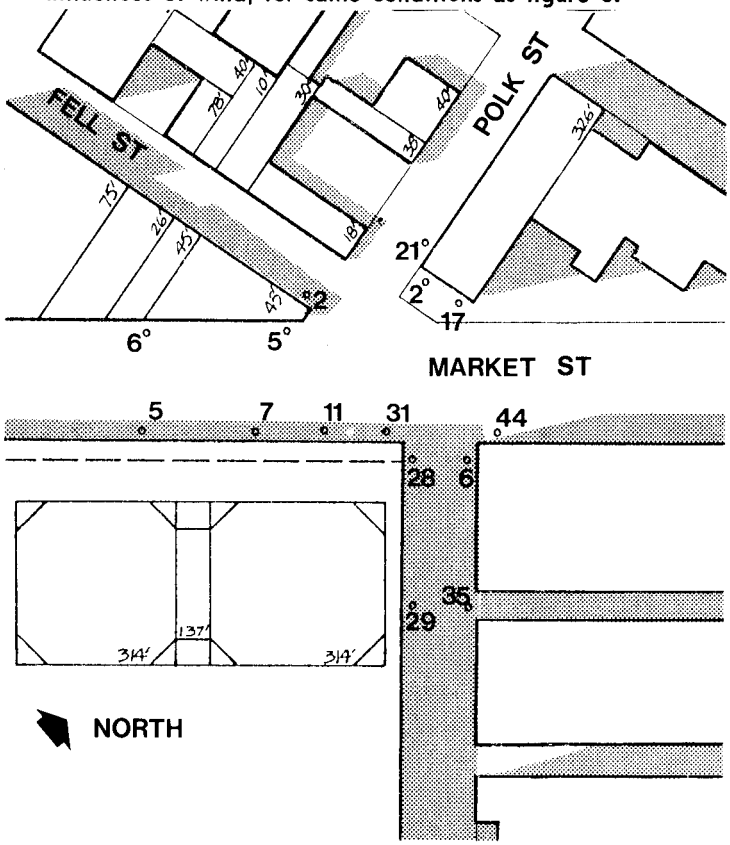
Discomfort frequencies calculated by using mechanical wind effects criteria are lower than those calculated by thermal prediction (fig. 7). There is also considerably more variation over the site, reflecting the varying strengths of the wind.

While ignoring temperature and sun-shade effects, the mechanical method provides a reasonable estimate of discomfort due to wind. Although the absolute values are known to be low, the pattern and relative values are both reasonable and useful. Sun-shade plots are included in the analysis to provide an intuitive judgment of thermal comfort as well.

IMPROVING SITE COMFORT

The comfort-prediction process described above estimates the levels of comfort to be expected at a site and

Figure 7.—Frequency of discomfort based on mechanical influences of wind, for same conditions as figure 6.



points out problem areas. This information can be used to design and locate building entrances, walkways, plazas, and balconies, as well as parks and recreational facilities. If the expected comfort levels are unacceptable, design modifications to improve conditions may be investigated.

Based on trials with wind tunnel models, design modifications within the site and budgetary limitations of the project are suggested. These modifications can range from changes in building height, bulk, or orientation to the provision of vegetation or landscaping to reduce winds.

For any given problem there is a range of possible solutions varying in effectiveness and cost. The procedures described in this paper may help optimize these factors. For example, roofing over a shopping mall would surely reduce winds, but construction of wind deflectors or latticework or use of vegetation may yield the same results at far less cost. The influence of such devices on sunlight should also be considered.

A model of the modified design is tested in the wind tunnel and the analysis of comfort repeated. Further modifications are again suggested and the process is repeated until a satisfactory design is obtained.

CONCLUSIONS

Prediction of discomfort frequency at a planned urban site is possible by using wind-tunnel tests of scale models to predict winds. There is insufficient knowledge at present to base discomfort frequencies on the thermal effects of climate. A simple prediction method, based on the better-understood mechanical effects of wind, yields results that are useful in the layout, orientation, and design of a project. This method provides a rationale and criteria for design modifications to improve outdoor comfort.

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Acknowledgment. The authors thank Nancy Tellefsen for many useful suggestions in the preparation of this paper.

Human Thermal Comfort in Urban Outdoor Spaces

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ABSTRACT.—Measurements of the physical environment of urban open spaces in Syracuse, New York, were used to compute the physiological responses of human users of the spaces. These calculations were then used to determine what environmental variables were both important to human comfort and susceptible to control by site design. Although air temperature and humidity are important to human thermal comfort, these variables were found not to be related in any way to site features; temperature and humidity in the central business district were uniform over space. The other variables found to be important to human thermal comfort are, in order of importance: solar radiation, infrared radiation, and wind speed. We found that all of these can be controlled to some extent by site design. Thus site design can be used to control human thermal comfort in outdoor urban spaces.

THE SUCCESS of an urban open space is influenced by many factors. The myriad components of the physical and social environment and the location of the space within the structure of the city all play primary roles. In this paper we focus on just one aspect of the physical environment: the thermal environment. We define the thermal environment as those physical-environment elements which determine human thermal comfort. This comfort is controlled by the energy exchange between the body and its surroundings and, in general, can be said to exist when the body can effortlessly maintain a constant deep body temperature of about 98.6°F. Thus the thermal environment consists of elements which determine heat exchange between the body and its surroundings: solar and infrared radiation, temperature and humidity of the air, and wind velocity. Of course, the activity of the person also plays a role, since as activity increases so does metabolic heat production.

The purpose of this study was to determine how various physical features of urban open spaces were related to human thermal comfort through their influence on the environmental elements. The basic question was "What features of the thermal environment, and hence human thermal comfort, are susceptable to control by site design?" Our study was a prelude to the development of design guidelines, some of which appear elsewhere in these proceedings *(Plumley)*.

METHODS

The experimental design of our study centered around the determination of human thermal comfort in various urban open spaces with different features. The role of various site features was determined from the study of their influence on the variables which determine thermal comfort. Comfort was determined by means of a model of the physiological response of humans to the environmental conditions as measured at

each site. Psychological comfort could then be inferred from the predicted physiological state.

Human Thermal Comfort

Thermal comfort is a psychological interpretation of the physiological state of the body and should not be confused with temperature sensation. Gagge *(1969)* summarized comfort and temperature sensation as follows:

1. For sitting, resting persons:
   a. A sense of neutrality, of comfort or pleasantness, always coincides with a state of thermal neutrality (maintenance of deep-body temperature at 98.6°F without regulatory effort via vascular constriction or dilation or sweating).
   b. Discomfort correlates best with skin temperature in cold conditions and with increased skin sweating in hot conditions.
   c. Temperature and comfort sensations do not behave the same way with changing environment. Temperature sensation changes more rapidly than comfort sensation and, cold discomfort changes more rapidly than does warm discomfort.

2. Under conditions where the subject is active the following changes in sensation occur:
   a. Temperature sensation in warm and cold conditions is best correlated with skin temperature and air temperature and is *not affected by the level of activity.*
   b. Warm discomfort is best correlated with increased skin sweating.

It is evident that skin temperature and sweating are the important sensible physiological reactions of the body to a thermal stress. Thermal stress is created when the net loss of thermal energy from the subject's body does not equal the production of heat by metabolism within the body. In order for deep body temperature to remain constant, this balance of heat losses and gains must be obtained. Under cold conditions the losses usually exceed the gains, and several physiological systems act to reduce heat loss from the body. Vascular constriction reduces blood flow to the skin, and, as a result, skin temperatures drop. Heat production can be increased by voluntary activity or by involuntary shivering. Under warm conditions the body is gaining more heat than it can dispose of without effort, and vascular dilation occurs, with the result that the skin warms. If this action is insufficient to balance the heat budget, then sweating will occur. If the sweat rate exceeds the ability of the environment to evaporate the moisture, the skin will become wet.

The exchange of heat between the body and the environment can take place in several ways (table 1). For each heat-flow route, we have listed the controlling environmental factors and the conditions which determine whether the flow of heat in the route is toward (source) or away (sink) from the body. To actually predict the thermal state of the body in any given situation, equations must be written for each of these routes, and the set of simultaneous equations which results must be solved for the condition of interest: skin temperature and/or skin wettedness.

We have used a relatively old model of physiological response developed by Belding and Hatch *(1955)* and improved by Lee and Henschel *(1963)*. This model computes a Relative Strain (RS) for any given environmental condition and level of activity. Lee and Henschel *(1963)* related the various levels of RS to psychological conditions of "comfort," "discomfort," "failure," etc. However, since all of these correlations have been developed for subjects *indoors,* caution must be taken in applying these comfort ranges to people outside.

The Relative Strain model is:

$$RS = \frac{\text{Evap. cooling required to maintain heat balance}}{\text{Maximum evap. cooling possible under existing conditions.}}$$

$$= \frac{M\,(I_2 + I_c) + 5.55\,(T_a - 35) + RI_a}{7.55\,(44 - P_a)}$$

where

M =	metabolic rate	Kcal $M^{-2}hr^{-1}$
I_a =	insulation of air	clo
I_c =	insulation of clothing	clo
T_a =	air temperature	C
R =	radiant load	Kcal $M^{-2}hr^{-1}$
P_a =	vapor pressure of air	mm Hg

and

$$\ln I_a = 0.5662 + 0.4026 \ln U + 0.0072 \ln U^2$$

U = wind speed mph

Radiant Loads (infrared and solar) are included by adding the energy absorbed to metabolism. This model was incorporated into an interactive computer program which computed RS from the environmental data gathered in each site. Table 2 shows the psychological response in terms of RS.

Site Selection

Figure 1 shows the Syracuse downtown area and the general location of the eight sites used by Vittum *(1974)*. For this report we will be discussing

Table 1.—Summary of heat flow between a body and its environment

Heat-flow route	Controlling environmental elements	Conditions for route being —	
		Source	Sink
Metabolism	Activity of subject	Always	——
Radiation			
Solar	Shade-producing elements	Daytime	——
Infrared	T_r, T_s	$T_r > T_s$	$T_r < T_s$
Convection	T_a, T_s, w	$T_a > T_s$ (increasing with increasing w)	$T_a < T_s$
Evaporation	P_s, P_a, w	—— (increasing with w)	$P_a < P_s$

T_s = Skin (clothing) temperature.
T_r = Radiant temperature of surroundings.
T_a = Temperature of the air.
w = Wind speed.
P_s = Vapor pressure of skin ($f(T_s)$.
P_a = Vapor pressure of air ($f(T_a$, RH).
RH = Relative humidity.

Table 2.—Interpretations of physiological responses to relative strain for the standard man (Lee and Henschel 1963, p. 24).

Relative strain	Physiological effects for the standard man
0—0.2	100 percent of individuals comfortable.
0.25	50 percent of individuals comfortable.
0.30	100 percent of individuals uncomfortable.
0.30—0.40	75 percent of individuals show stress.
0.40+	100 percent of individuals show distress.
0.40—0.50	50 percent of individuals show signs of physiological failure.
0.50—0.60	100 percent of individuals show signs of physiological failure.
0.60+	Responses approach or exceed range within which system experiences breakdown.

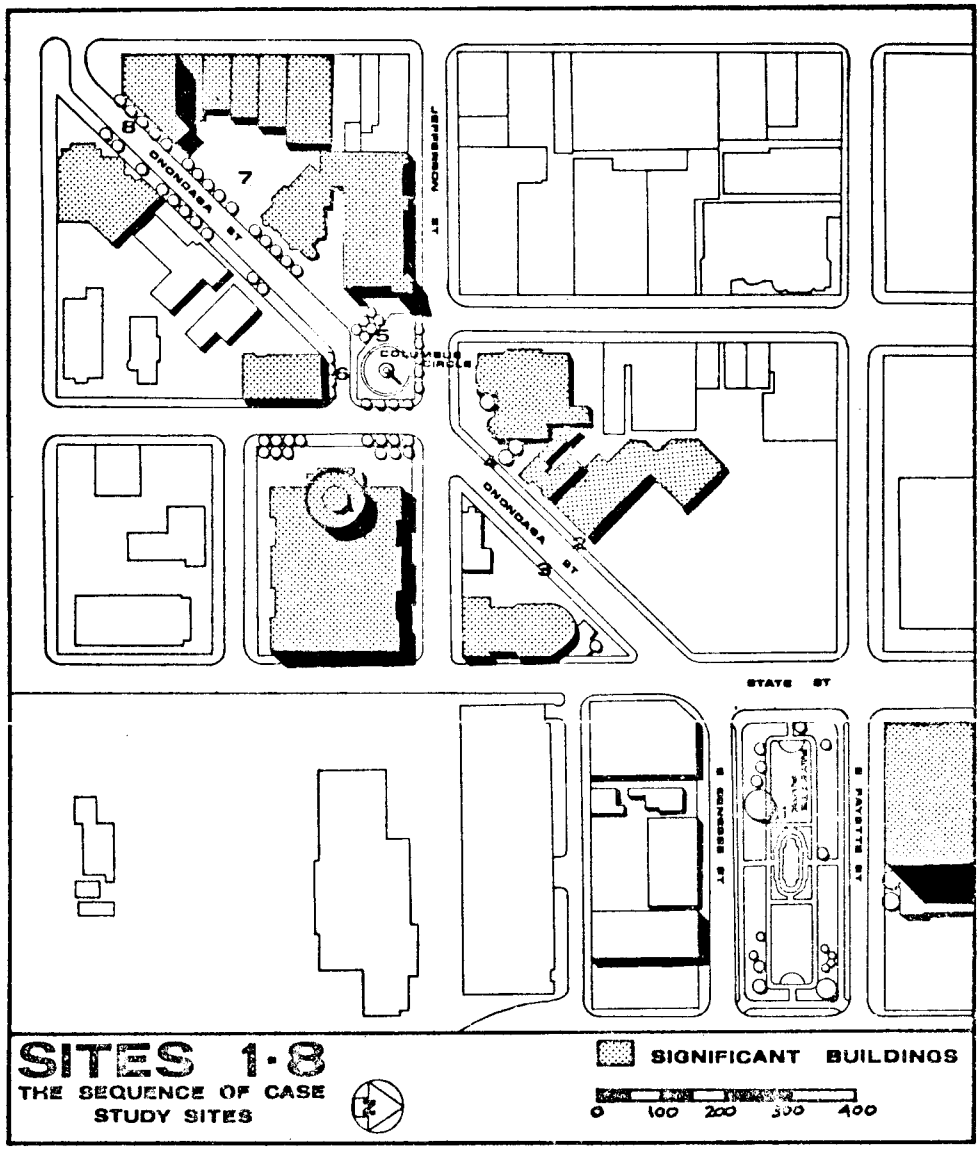


Figure 1.—Plan of the study site, showing the location of sites 1 to 8 as well as the significant buildings.

only four sites (1, 2, 6, and 7), which are shown in figures 2, 3, 4, and 5.

Site 1 is located in a park with very little enclosure, since most of the surrounding buildings are only two to three stories high. The ground surface at the site is grass. Table 3, which lists the view factors for the predominant surfaces at each site, shows that the surfaces as seen by a person at this site are nearly evenly split between sky and grass. Site 2, located on the sidewalk in a fairly open space on Onondaga Street, has nearly the same view of the sky and ground, but the ground surface is primarily concrete. Site 6, located on the north side of a building within Columbus Circle has a relatively low view of the sky since the site is more enclosed, as indicated by the high view factors for the surrounding buildings and trees. The ground surfaces are brick and asphalt. Site 7 has a high view of the sky, and the ground surface is

Figure 2.—Site 1. 'X' marks point where measurements were taken and for which view factors were calculated.

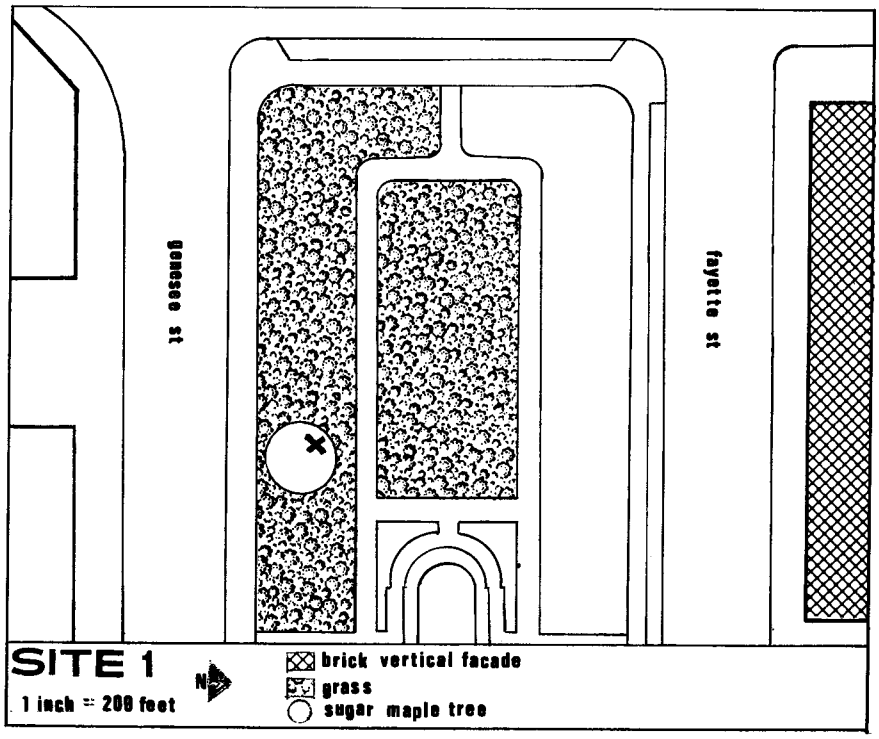


Figure 3.—Site 2.

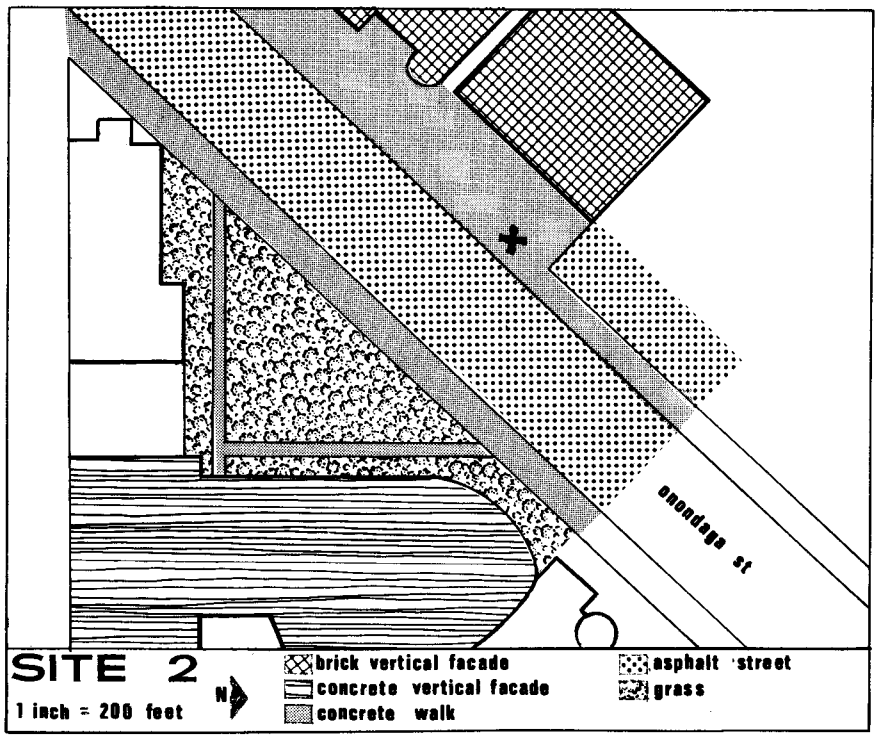


Figure 4.—Site 6.

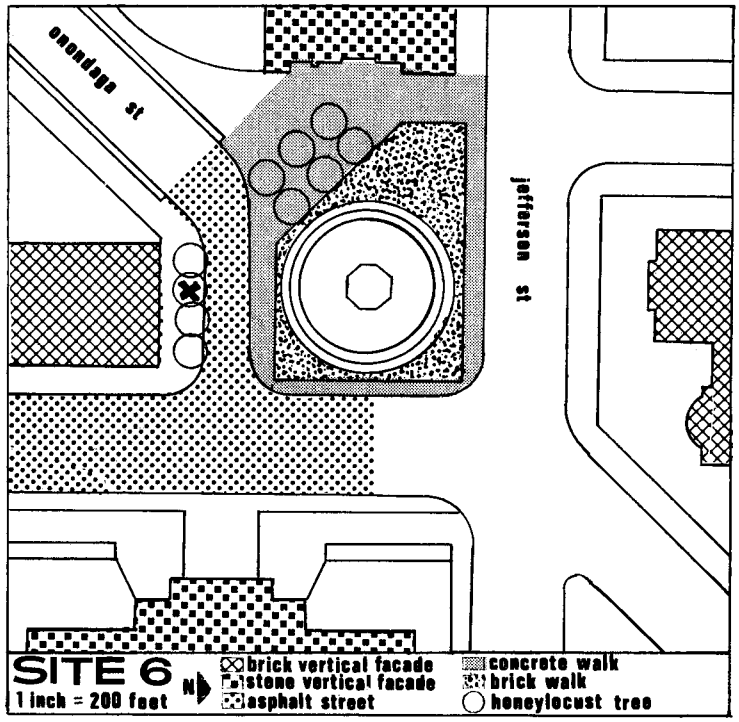


Figure 5.—Site 7.

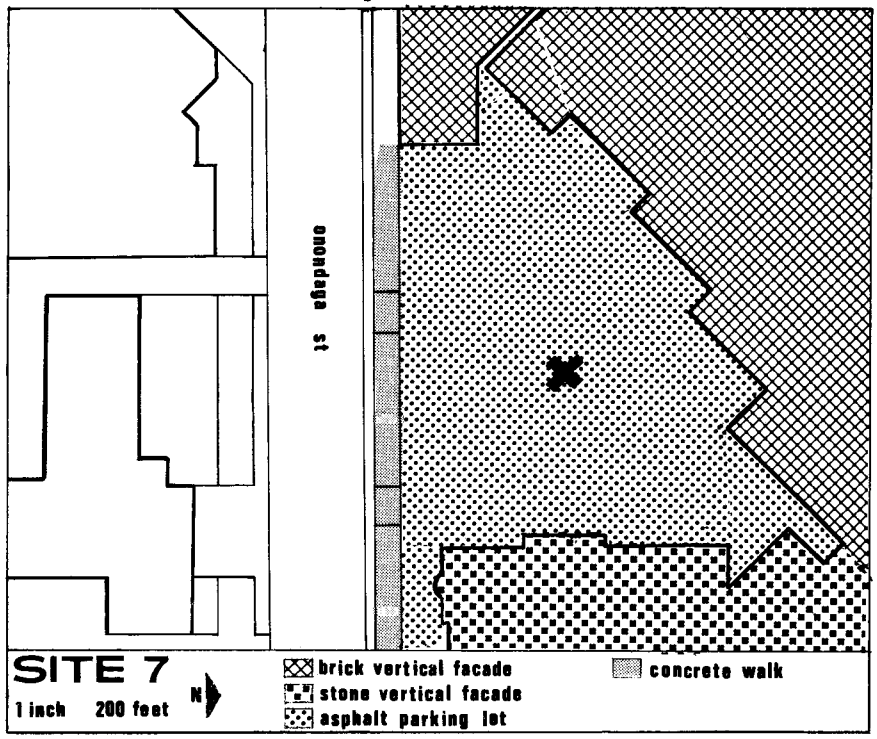


Table 3.—View factors between subject standing at site location and surrounding surfaces.

Site No.	Surfaces									
	Sky	Street	Walks		Tree(s)	Grass	Building Facing			
			Brick	Concrete			N	E	S	W
1	39	—	—	—	7	50	4	—	—	—
2	38	4	—	42	—	—	—	10	—	5
6	14	8	34	—	10	—	21	7	1	4
7	36	50	—	—	—	—	—	2	5	6

primarily macadam. Vegetation is a feature only in site 6, which is located beneath a row of street trees.

Environmental Measurements

A portable instrument system was used to measure air temperature and humidity, solar radiation, and wind speed at each site. The radiant load was computed from the measured solar radiation and from knowledge of the sun's position in the sky at the time of measurement. The infrared load was computed from view factors, and surface temperatures were measured with a radiation thermometer. The view factor is the proportion of the total spherical field of view from a subject taken up by the surface or object of interest. The infrared exchange between the subject and the surface is proportional to the view factor and the difference in temperature between the subject and the surface (table 3).

RESULTS AND DISCUSSION

Table 4 lists environmental and comfort data typical of the four sites at three times of day: morning, noon, and evening.

The air temperature and humidity data for each measurement period show a surprising uniformity once the trend in temperature caused by the time it took to move from site to site is removed. Note that temperatures are increasing with site sequence in the morning and decreasing with site sequence in the evening. This uniformity of temperature prompted us to investigate further the uniformity of temperature within the Syracuse CBD. This was done simply by moving around very quickly with a single psychrometer (Bendix Psychron). This procedure indicated that the temperature at any given spot could vary by as much as 6°F in a short time due to changes in solar radiation caused by clouds. However, these changes took place over a large area; and moving from tree shade, to sun lit areas, to building shade showed that the temperature is not an element of open-space environment that can be controlled or moderated by site design. The same pattern was true for relative humidity.

Solar radiation showed considerable variation from site to site. Comparison of the radiation figures in table 4 with the maps of the sites shows that the variation in solar radiation is due primarily to shading by buildings or vegetation.

The IR radiation load, as listed in table 4 or as expressed as the mean radiant temperature (MRT) of the space obviously varies with the time of day. During the day site 7, which was located in an open macadam parking lot, showed the highest IR load (MRT) because of the high view factor between the person and the blacktop surface (table 3). No shade is provided by buildings or vegetation. Site 1, in the open grassy park, shows the lowest IR radiant load, again due primarily to the nature of the surface; grass in this case. Sites 2 and 6, both street sites, tend to behave in a similar way in relation to infrared radi-

Table 4.—Summary of environmental conditions and relative strains

Variable	0800—23 Aug 1973				1300—10 Sept 1973				2130—22 Aug 1973			
	1	2	6	7	1	2	6	7	1	2	6	7
Dry bulb temp. (°C)	15	16	17	18	22	24	24	24	15	15	15	13
Relative humidity (%)	65	63	60	59	41	35	36	37	73	67	75	77
Solar radiation (Kcal/M²hr)	444	168	84	360	84	648	96	600	—	—	—	—
IR radiation (Kcal/M²hr)	–51	–58	–55	–32	–69	–32	–35	–10	–98	–82	–71	–87
Wind speed (mph)	1.8	2.1	3.4	2.1	2.7	1.4	1.8	1.7	1.9	2.1	2.3	1.5
Relative strain	– 0.26	– 0.30	– 0.28	– 0.22	– 0.18	– 0.01	– 0.11	– 0.02	– 0.36	– 0.33	– 0.35	– 0.38
w/wind=zero	– 0.23	– 0.26	– 0.25	– 0.18	– 0.16	– 0.01	– 0.10	– 0.01	– 0.36	– 0.32	– 0.34	– 0.38
w/solar=zero	– 0.30	– 0.30	– 0.28	– 0.25	– 0.18	– 0.11	– 0.12	– 0.10	– 0.36	– 0.33	– 0.35	– 0.38
w/IR=zero	– 0.20	– 0.20	– 0.25	– 0.20	– 0.14	– 0.02	– 0.08	– 0.02	– 0.30	– 0.27	– 0.31	– 0.31
Mean radiant temperature (°C)	20	19	19	24	16	24	23	30	10	13	16	15
Weather condition	Partly cloudy, cool, breezy				Clear, cool, breezy				Clear, cool, breezy			
Sky temperature	18				5				5			

ation. According to table 3, site 6 "sees" considerably less sky, which on these days had an apparent radiant temperature of about 5 to 8°C, than site 7. Therefore it is not surprising that the infrared load in site 7 is more negative (MRT is lower) than in site 6.

Wind speed was variable over both site and time. The urban surface wind tends to be gusty but with a low average velocity. Wind speeds greater than 8 mph were rare. Wind direction was also variable and did not seem to be strongly related to the wind direction above the buildings as indicated by flags.

The lower part of table 4 lists relative strain as calculated for each site by using the environmental variables listed and also the relative strain which would occur if (1) the wind speed were reduced to zero, (2) the solar radiation were reduced to zero, and (3) the infrared radiation load were reduced to zero. These manipulations allowed us to determine the relative importance of the variables. Air temperature and humidity were not modified since they had already been shown to be inalterable by design.

Since the relative strains are all negative, we are dealing with a cool situation; the body requires more heat to achieve balance between inputs and outputs of thermal energy. Unfortunately we do not have any data relating the negative physiological strain to the psychological measure of comfort. However, we do know that to conserve heat the body will constrict the vascular system of the skin with the result that skin temperature is lowered. As mentioned above, cool discomfort is directly related to skin temperature, and the sensation of cool discomfort changes more rapidly below the neutral skin temperature (comfort condition) than above that point. Since we know that on the warm side, relative strain values of between 0 and 0.2 are "comfortable," and that discomfort increases with increasing relative strain (table 2), we can safely assume that the same will occur below

thermal neutrality. In other words, we can use table 3 with absolute values of relative strain for a rough indication of comfort.

Wind speed had relatively little effect on relative strain (RS). The average change in relative strain when wind was reduced to zero was only 0.02 or about 10 percent of the RS value. The effect of wind does increase in magnitude with increasing strain, however: compare site 7, 0800 and site 2, 1300.

The effects of solar radiation are quite large as can be seen by comparing sites 1 and 2 at 0800 (RS of —.26 and —.30 respectively) and by studying the difference in relative strain when solar radiation is eliminated (see site 1, 0800; site 2, 1300; site 7, 1300 for example). The presence or absence of solar radiation has a strong influence on human thermal comfort.

At all sites the infrared radiation balance was negative; that is, heat is flowing away from the body, because all surfaces have temperatures below 30°C (skin/clothing temperature). Sites which have large view factors with sky will tend to have larger negative infrared radiation balances since the sky is usually cold, particularly on clear days. Thus sites 1 and 7 show a strong improvement in relative strain when the infrared radiation balance is reduced to zero. On the other hand, site 6, which has only 16 percent of its view occupied by sky (table 3) shows little change when the infrared balance is reduced to zero. Note that as the apparent sky temperature decreases, the effect of eliminating the infrared heat balance increases.

CONCLUSIONS

These data indicate that solar radiation, infrared radiation, and wind are important to human thermal comfort in urban outdoor spaces and, further, that they can be controlled through site design. Trees and other vegetation can be used to provide shade during hot periods to reduce the input of solar energy to the user's body. If spaces are used during cooler periods, then shading should be kept to a minimum. Structures, of course, can be used for the same purpose. Vegetation can be used to screen the user from sources of infrared radiation such as sun-heated walls and streets during the warm season and to limit infrared radiation loss to cold surface such as the sky during cold periods. Although it is not very important in the city under warm conditions, wind speed can play an important role during the cold season as is indicated by the popularity of wind-chill factors in winter weather reports. Various arrangements of vegetation and structure which could be used to reduce the heat losses due to high winds in winter would have little effect on RS in summer.

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Effect of Synthetic Surfaces and Vegetation in Urban Areas on Human Energy Balance and Comfort

by THOMAS F. STARK *and* DAVID R. MILLER, *graduate assistant and assistant professor of natural resources, The University of Connecticut, Storrs, Conn. 06268.* *This research was supported in part by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Studies.*

ABSTRACT.—The thermal balance of a standard man was quantified for a variety of urban and rural summer daytime microclimates. The resulting net heat-load data were correlated with the relative amounts of vegetation and synthetic materials at each site. By extrapolating these results, it is possible to estimate the expected heat load of a proposed development before it is built.

THERE IS LITTLE DOUBT that the day-to-day weather as well as the overall climatic pattern in an area affect which activities people pursue, how well they perform, and generally whether they feel comfortable *(Huntington and Cushing 1924)*. Recently Belding and Hatch *(1955)* and Tromp *(1966)* definitely linked climatic variables with human comfort when they observed that climatic parameters such as air temperature, humidity, and wind speed cause distinct and repeatable human physiological stress responses.

The objective of our study was to examine and quantify the thermal exchanges between a theoretical subject and several urban- and suburban-type sites to determine which were the most and least comfortable and why. From the results, specific factors of site design that significantly affect human comfort can be identified and utilized by city planners for future development.

DETERMINING HUMAN THERMAL COMFORT

Inequalities in the temperatures of terrestrial objects results in an exchange of energy between the objects as they approach thermal equilibrium with each other. The major means by which energy is exchanged are radiation (R), convection (C), conduction (G), and the evaporation or condensation of water (LE). Over a sufficiently long period of time, the summation of all the energy gains and losses by an object or human subject will equal zero:

$$R+C+G+LE=0 \quad [1]$$

The instantaneous rate of heat gain or loss, which must be compensated for to maintain the body core-temperature constant, has been established as an important factor in human comfort. But quantification of the instantaneous net heat load for human subjects is complicated by the facts that each of the processes of equation 1 act in not one but several ways and that clothing alters the exchanges in a variety of ways. Fanger *(1970)* presented a similar model for a human subject that demonstrates how a single process such as evaporation is complicated in the human energy balance problem:

$$M+R+G+G+Ed+E_{sw}+E_{re}+L+C=0 \quad [2]$$

where:

- M = Metabolic heat production.
- Ed = Heat loss by skin diffusion.
- E_{sw} = Heat loss by evaporation of sensible sweat.
- E_{re} = Latent respiratory heat loss.
- L = Dry respiratory heat loss.

In equation 2 the single evaporation term of equation 1 (LE) has been broken into three separate terms (Ed, E_{sw}, and E_{re}), each representing a form of energy exchange by evaporation that must be determined independently.

Before this relationship was derived, the rates of energy gain and loss, which determined the limits of the comfort zone, were established by asking a sample of people how they felt in a series of test environments. Those environments in which subjects most frequently said they were comfortable were then designated as comfortable; and upper and lower limits were established. Belding and Hatch *(1955)* then evaluated these limits, using a relationship similar to equation 2; and they concluded that the limits of the human comfort zone are ±500 calories per minute for an average subject.

MATERIALS AND METHODS

Data Collected and Site Description

Data were taken in June and July 1974 on The University of Connecticut campus at Storrs (latitude 41°47′30″, longitude 72°14′33″W, average elevation 215 meters). The University campus represents an urban-like environment built to be esthetically pleasing and surrounded by undeveloped woodlands. Eight sites that were felt to be microclimatically dissimilar were selected. Figures 1 through 7 are photographs and scale drawings that cover full 360° views of these sites.

Site 1 is not pictured, but is a typical area beneath the canopy of a 20-m-tall black oak *(Quercus velutina)* forest with moderate undergrowth.

At each site wet and dry bulb temperatures were measured with a Bendix aspirated psychrometer, wind speed with a Hasting's omnidirectional air meter, and surface temperatures of facing solids with a Barnes PR-10 infrared thermometer. Solar radiation was monitored with a Kipp pyranometer located in the northwest corner of site 2.

Data were taken at each site once every 2 hours of each data day beginning at site 1 and progressing sequentially through site 8. At the end of each run, measurements were repeated at site 2 to give some indication of how conditions had changed during the course of the data collection. Data runs were begun at 0730, 0930, 1130, 1330, 1530, and 1730 solar time. Transit time from site to site was approximately 3 minutes, and the total time elapsed from the start to the finish of a data run averaged 1 hour. A total of 8 data days were obtained for use in later analysis.

Data Reduction

Equation 2 was modified by splitting the radiation term into a solar radiation component (S) and an infrared radiation component (IR). The solar component was then evaluated, using the techniques of Underwood and Ward *(1966)*, giving the working model:

$$S-(r+t)\,S+M+IR+G+Ed+E_{sw}+E_{re}+L+C=0 \qquad [3]$$

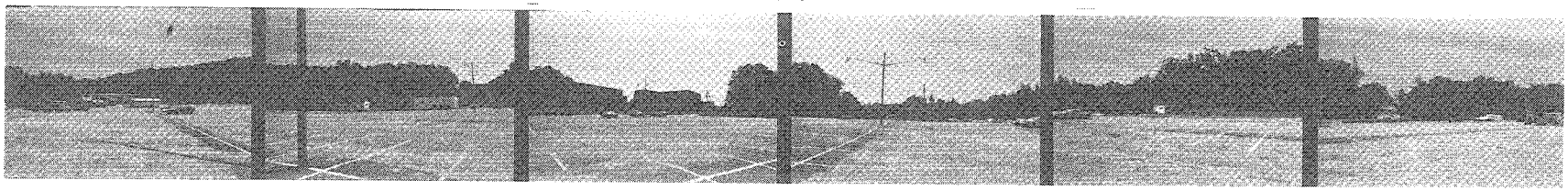
where:

r = the reflectivity of the subject to solar radiation.

t = the transmissivity of the subject to solar radiation.

To quantify equation 3 and utilize it to compare the sites it was necessary to make a number of assumptions to rule out the variability between human subjects. For this study, the subject was assumed to be a young male, aged 20 to 35 years, with a surface area of 1.8 m^2, who was walking at 1.5 m sec^{-1} and whose orientation with respect to the sun was constantly changing. His skin temperature was assumed, from the basis of a literature review, as 32°C. A corresponding clothing temperature of 35°C was established from supplementary experimentation in which the actual temperature differences between the skin and outer clothing surfaces were monitored and found to average 3°C. Con-

Figure 1.—Site number two. (+) denotes measurement site.



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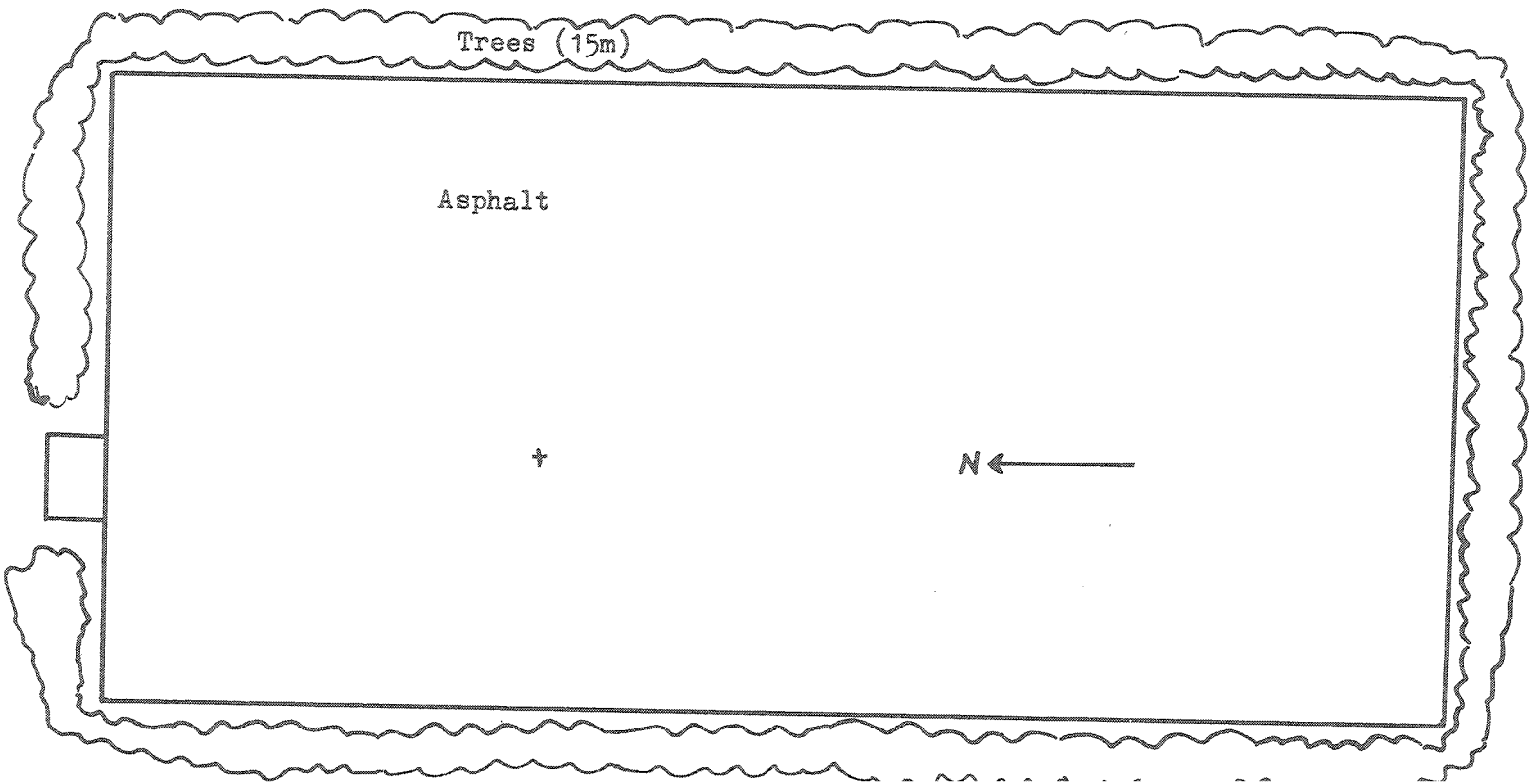
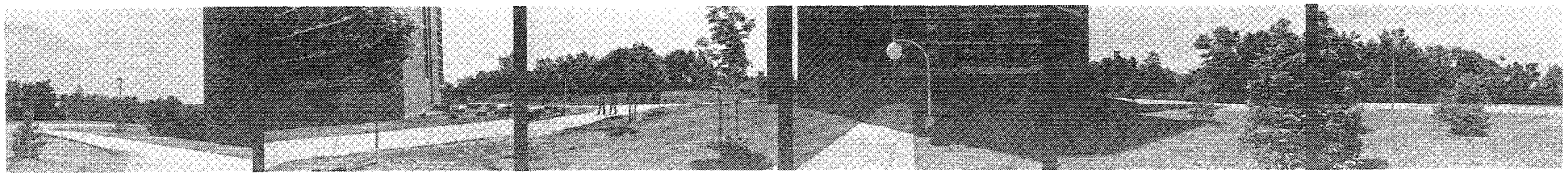


Figure 2.—Site number three. (+) denotes measurement site.



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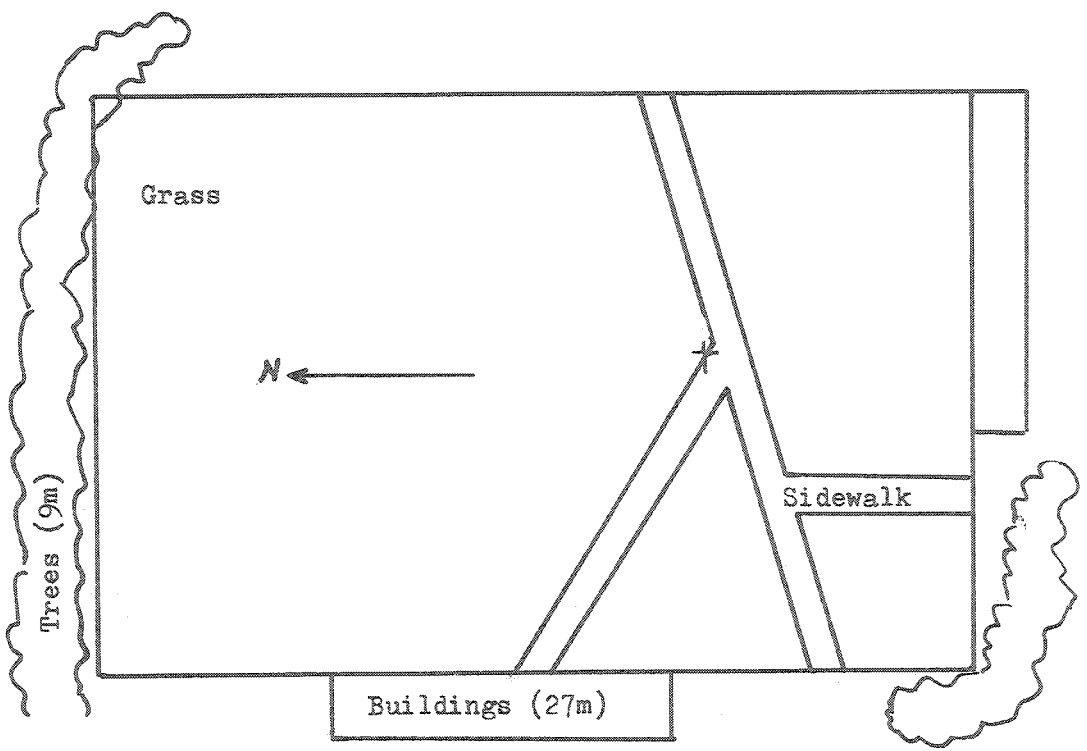
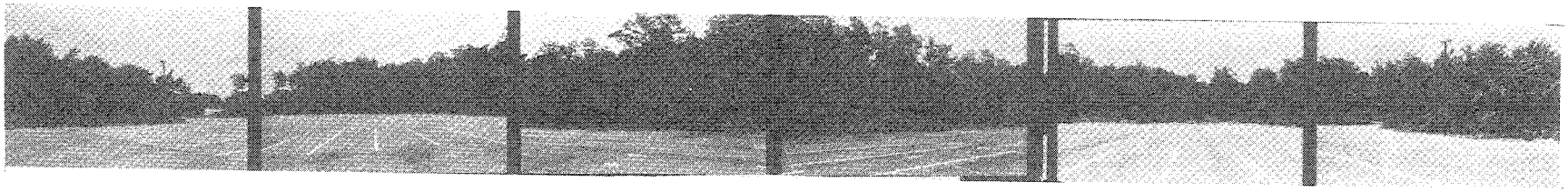


Figure 3.—Site number four. (+) denotes measurement site.



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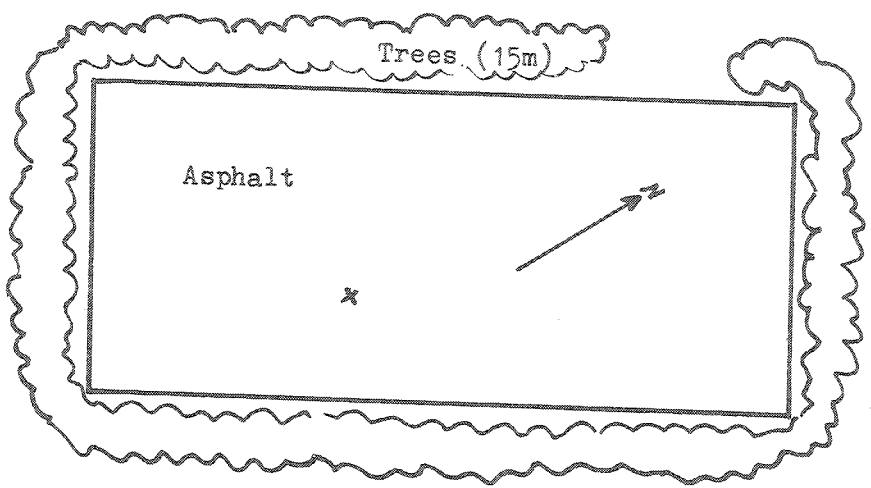
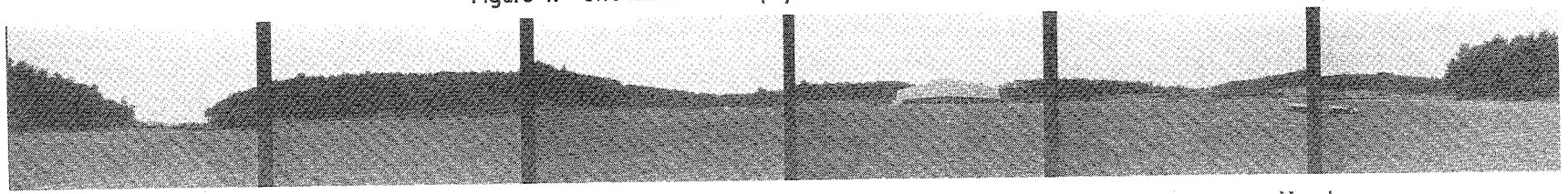


Figure 4.—Site number five. (+) denotes measurement site.



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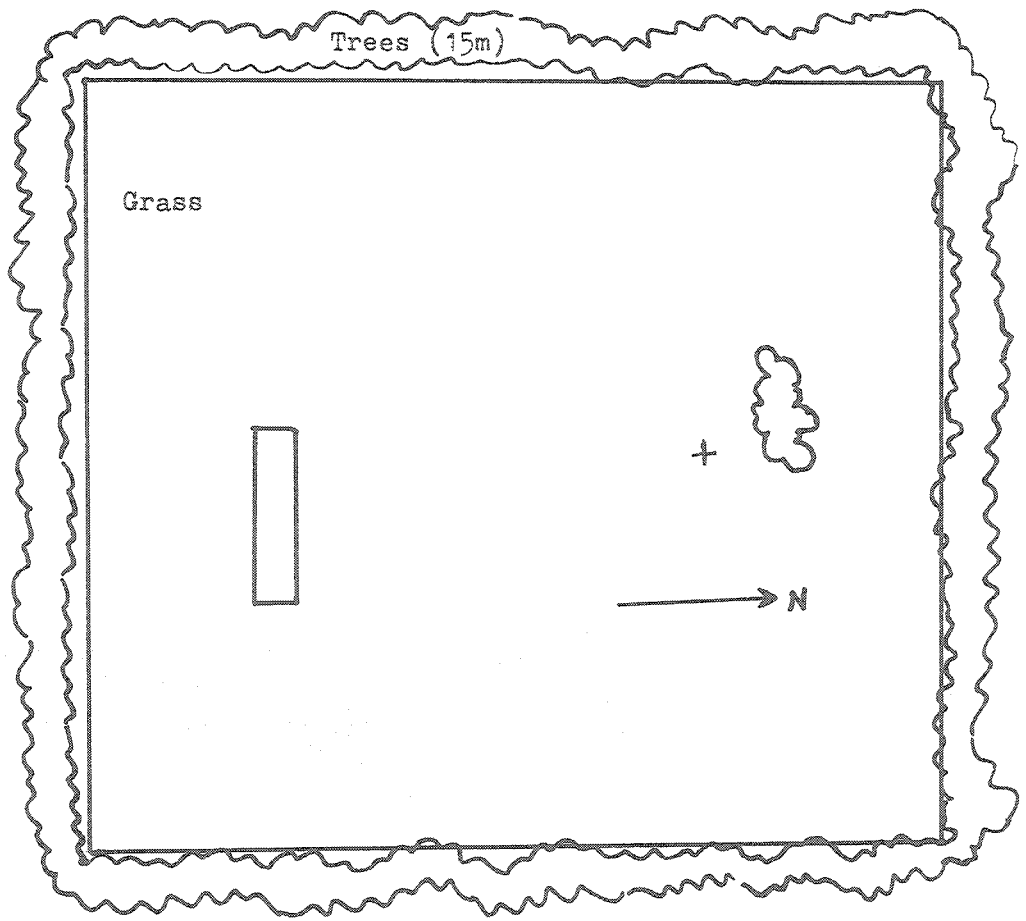
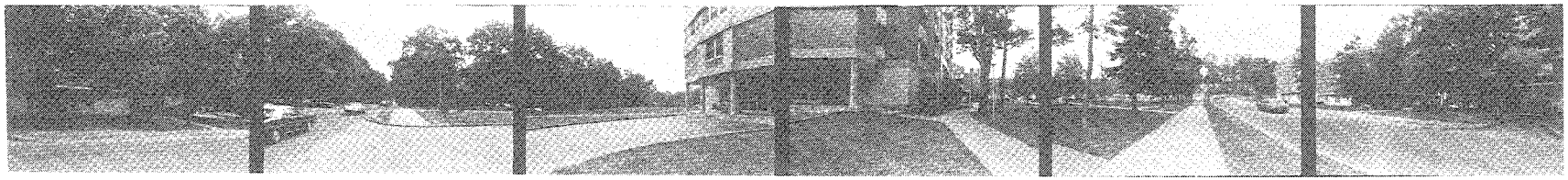


Figure 5.—Site number six. (+) denotes measurement site.



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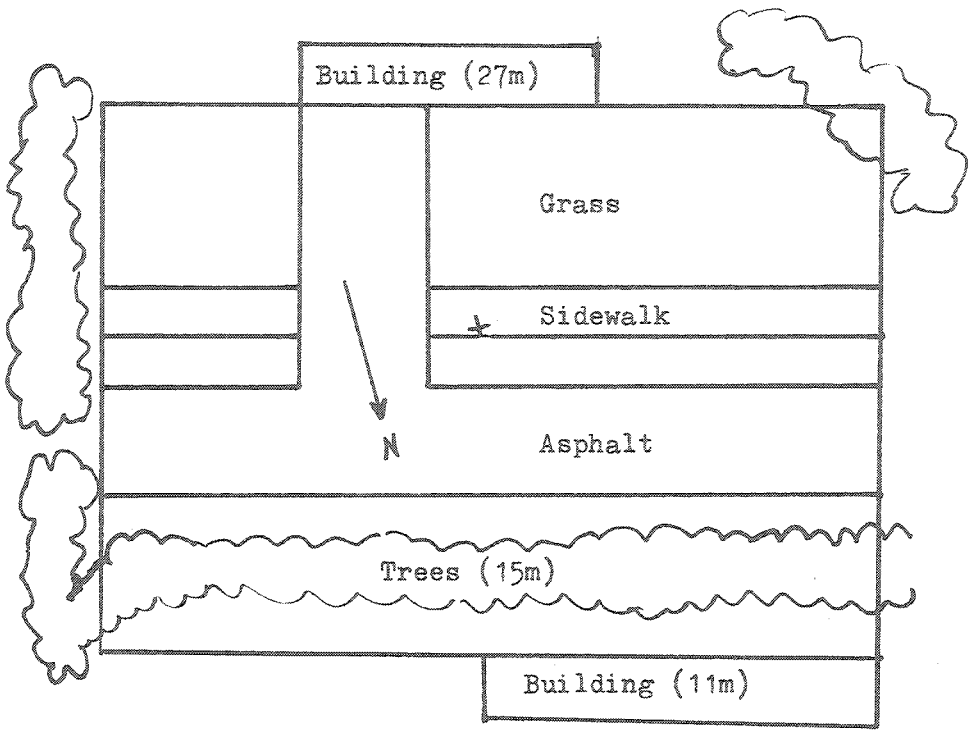
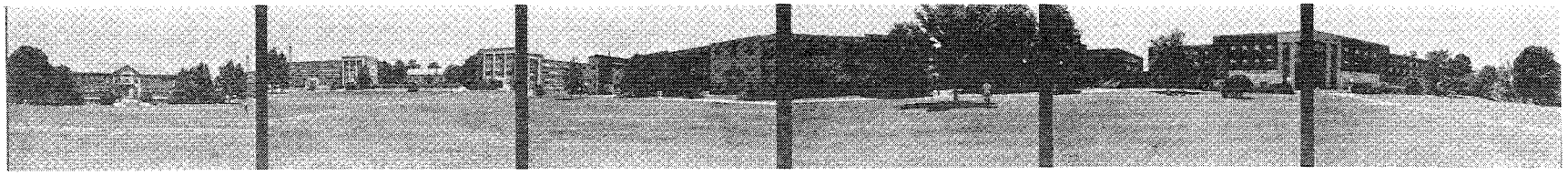


Figure 6.—Site number seven. (+) denotes measurement site.



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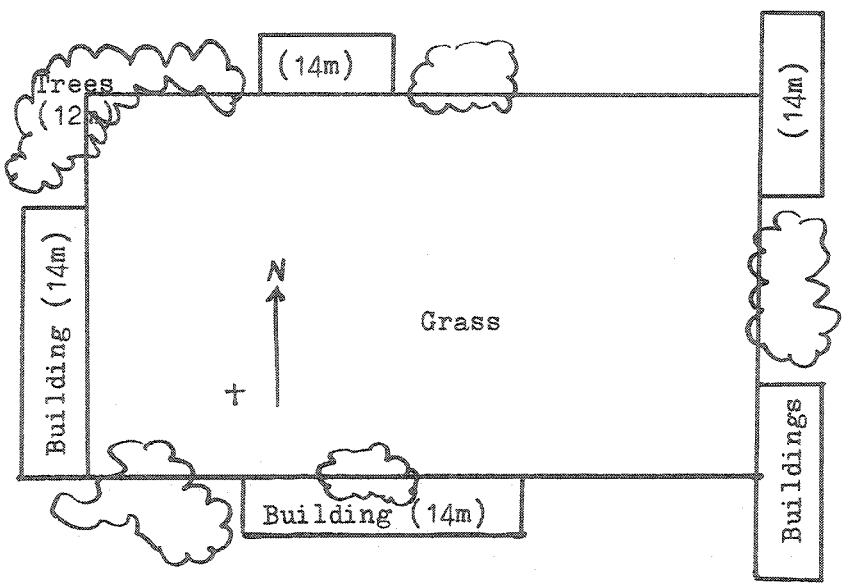
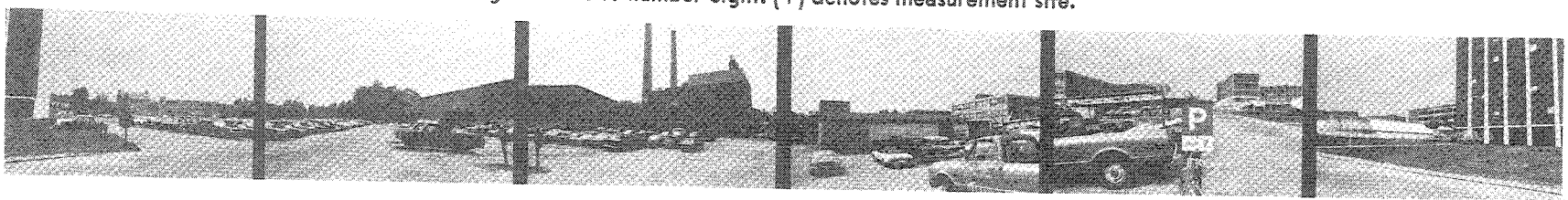
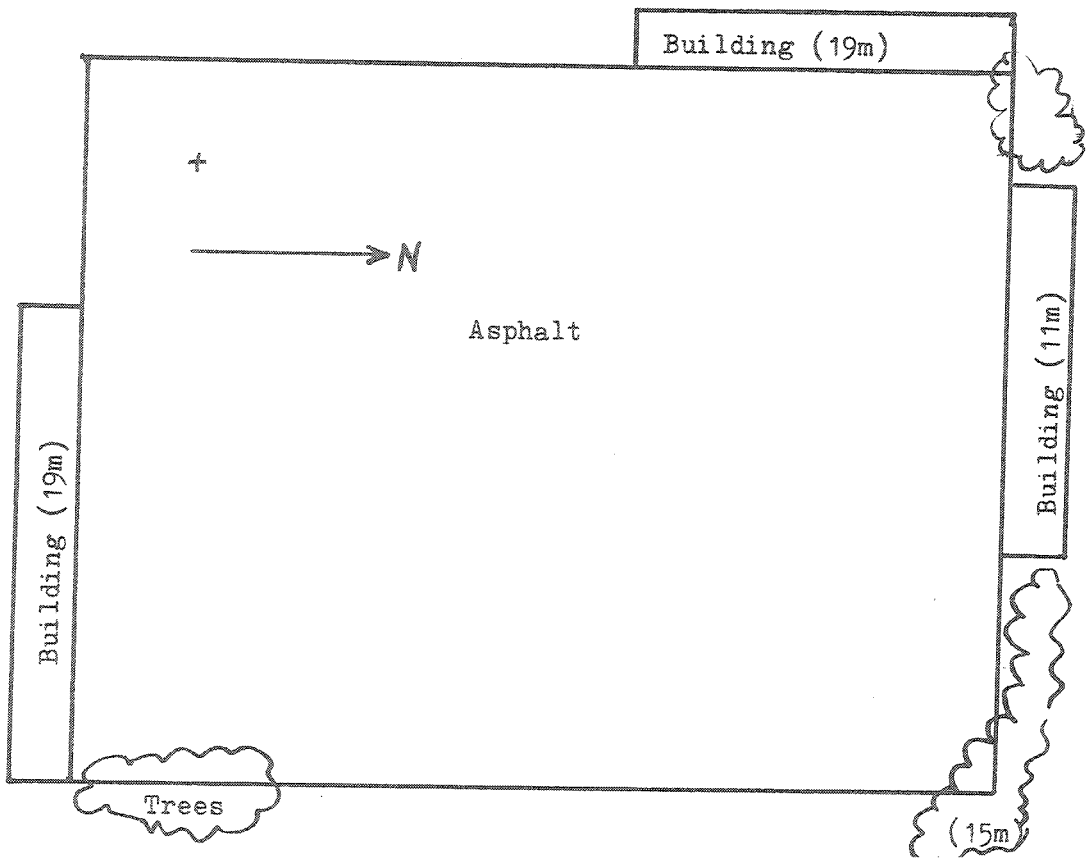


Figure 7.—Site number eight. (+) denotes measurement site.



North East South West



duction (G) for a standing subject was assumed negligible. Finally, it was assumed that the subject would be in complete equilibrium with his clothing so that any heat gained or lost at the outer surface of the clothing would represent an equal heat gain or loss to the subject.

After making these assumptions and reducing all units to cal min^{-1} for the subject, we devised a working model from equation 3:

$$(DRA)\ (s)\ .8+M+Vf_{s\text{-}o}{}_{n}\ (Ro_n—R_s) + 10.56\ (36—pa) + 3.8\ (44—Pa) + 2.3\ (34—ta) + 33.18hc\ (35—ta) = \text{net heat load before evaporation of sweat (cal. } min^{-1}) \quad [4]$$

where:

DRA = The direct radiational area determined, using the work of Underwood and Ward *(1966)*.

$Vf_{s\text{-}o}{}_{n}$ = The view factor between the subject and the indicated object (n) in the environment, determined by using the graphic methods of Fanger *(1970)*.

R_s and Ro_n = The radiosites of the subject and objects respectively calculated by the Stefan-Boltzmann Law: $R = \epsilon\sigma T^4$, where the emissivity (ϵ) was assumed unity, σ is the Stefan-Boltzmann constant, and T is surface temperature (°K).

Pa = Air vapor pressure (cm Hg).

ta = Air temperature (°C).

hc = Convective coefficient, using Fanger's *(1970)* equation: $hc = 10.4\sqrt{v}$, where v is the wind velocity (m sec^{-1}).

M = Metabolic heat production, assumed constant at 3016 cal min^{-1}.

RESULTS AND DISCUSSION

The sites were evaluated with equation 4 and were compared in terms of relative humidity, vapor pressure, wind speed, and air temperature as well as net heat load. Figure 8 shows a graph of the net heat loads for each site averaged for all 8 test days. On this graph, points above the x-axis represent positive heat loads or conditions in which a subject must get rid of excess heat by evaporation of liquid sweat in order to be comfortable. Thus, those sites that reach the greatest positive values and are above the x-axis the longest time during the day are the most uncomfortable. Sites 2, 4, 6, and 8 were singled out in this manner.

Table 1 gives the percentage of the total view of each site represented by various groupings of materials and averaged midday air temperatures, humidities, and wind speeds. Despite the obvious physical differences among sites 1 to 8, the average air temperature, vapor pressure, and wind speed varied little. A comparison of the view factor information in table 1 with the net heat-load data revealed a correlation between midday net heat loads (0930 through 1530) and the percentage view factors of synthetic and vegetative materials.

Regression analyses were made of the importance of the view-factor groupings of vegetation, synthetic materials, sky, and not sky in determining net heat loads. Separate analyses were made for day-long averages, for transition periods (0730 and 1730), and for midday periods. Table 2 shows some results of these regressions.

Table 2 shows that there was very little correlation between net heat load and either vegetative or synthetic view-factor groupings during the transition periods when surface temperatures were relatively low. Further, the correlations for individual days and times became higher as the overall synoptic conditions became hotter. This indicates that the

Figure 8.—Average net heat loads for June and July data days.

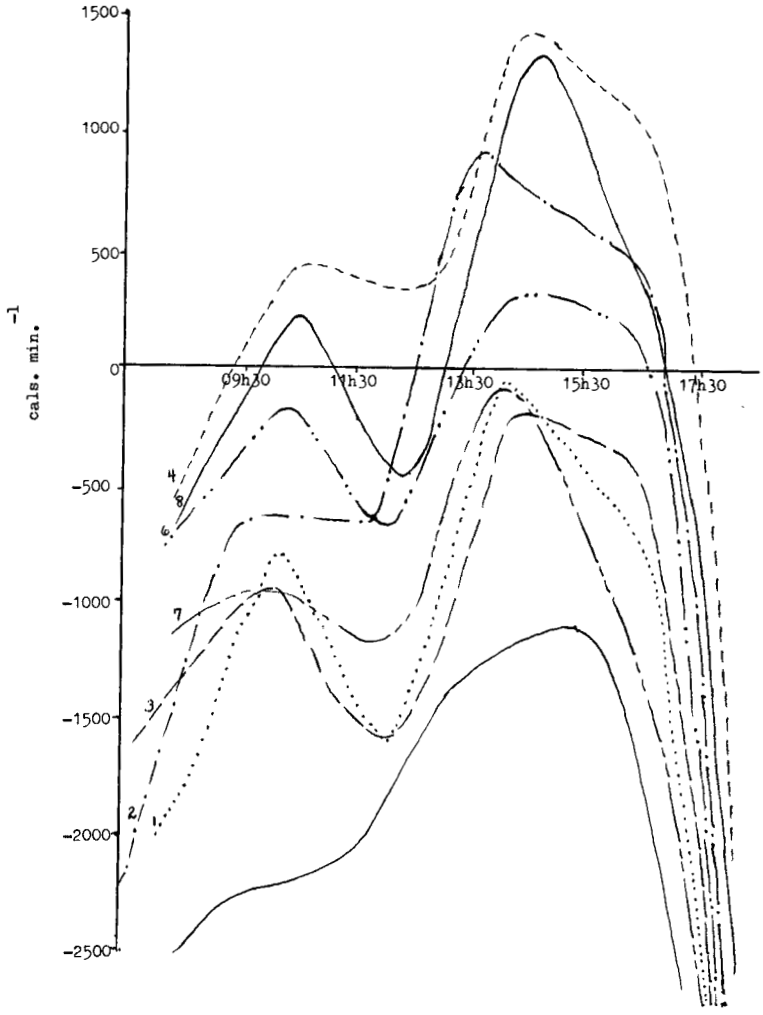


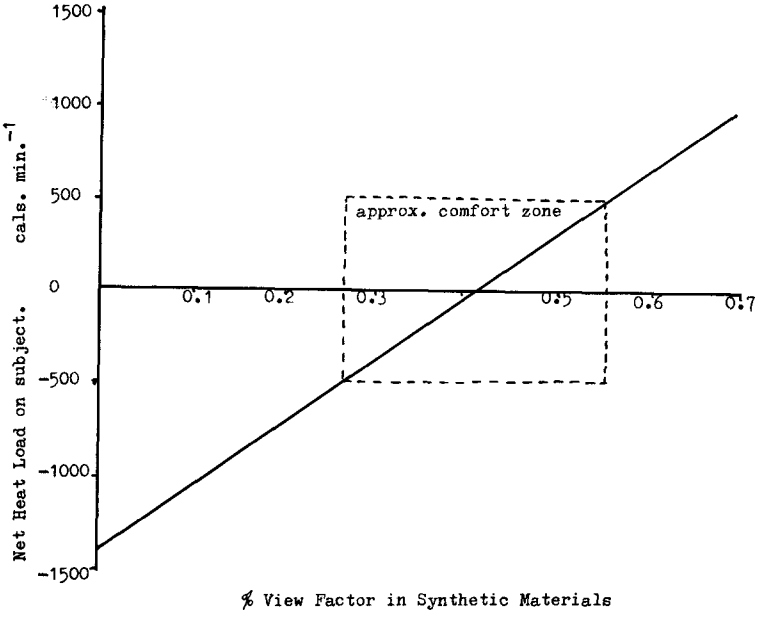
Table 1.—View-factor descriptions of sites and their average midday air temperature, vapor pressure, and wind speed

Site	Sky	Vegetation	Synthetic material	Average midday		
				Air temperature	Vapor pressure	Wind speed
	Pct.	*Pct.*	*Pct.*	*°C*	*cmHg*	*m sec*$^{-1}$
1	0	100	0	24°	12.0	0.46
2	49	3	48	26°	10.4	.91
3	24	57	19	26°	10.2	1.06
4	28	24	48	27°	10.2	.73
5	50	50	0	26°	10.5	.94
6	27	37	37	27°	10.1	.96
7	40	46	14	26°	10.3	.92
8	43	0	57	27°	10.3	.98

Table 2.—Partial results of the statistical correlations between the indicated view-factor category and averaged net heat loads

Period	View-factor category	Sites	r	$S_{y \cdot x}$ (cal. min^{-1})
Midday,				
June and July . . .	Synthetic materials	1-8	0.88	334
	Synthetic materials	1-4, 6-8	.93	270
	Vegetation	1-8	— .88	338
	Vegetation	1-4, 6-8	— .87	359
Transition,				
June and July . . .	Synthetic materials	1-8	.69	361
	Vegetation	1-8	— .46	420

Figure 9.—Average midday heat load versus the fraction of view in synthetic materials.



effect of these view-factor groupings in the urban microclimate increases as the overall climatic stress becomes more and more positive.

During the midday periods, correlations between net heat load and vegetative and synthetic categories were high. The regression analysis of the midday heat loads versus the percentage view factor in synthetic materials suggests that 87 percent of the variation in heat load from site to site can be explained by changes in the percentage view of synthetic materials.

Figure 9 shows this empirically defined relationship between the view-factor grouping of synthetic materials and midday net heat loads:

$$\text{Net heat load} = -1463 + 3574\ Vf_{syn.} \quad [5]$$

By reading the percentage of the view factor present, at a proposed site, of synthetic materials from the x-axis, an estimate of the expected heat load can be read from the point of intercept with this line. Given relationships of this nature, one should be able to design a site to fall within the comfort zone by manipulating vegetative shields and building spacing.

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Design of Outdoor Urban Spaces for Thermal Comfort

by HARRIET J. PLUMLEY, *research assistant, School of Landscape Architecture, State University of New York College of Environmental Science and Forestry, Syracuse, N. Y.* *This research was supported in part by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Studies.*

ABSTRACT.—Microclimates in outdoor urban spaces may be modified by controlling the wind and radiant environments in these spaces. Design guidelines were developed to specify how radiant environments may be selected or modified to provide conditions for thermal comfort. Fanger's human-thermal-comfort model was used to determine comfortable levels of radiant-heat exchange for various activities, clothing types, and climatic conditions. A comparison of these radiant quantities with measured and calculated quantities of radiant exchange expected for a person in urban spaces revealed several design guidelines.

EFFORTS BY PUBLIC AGENCIES and private interest groups to revitalize the central business districts in American cities have often included large expenditures for outdoor pedestrian spaces. Many such amenity spaces have failed to receive more than light use. This failure has been attributed partly to a general disregard for the physical-comfort needs of the users *(Whyte 1972)*. The need for thermal comfort is ubiquitous, but it seems often to be forgotten in the designs of outdoor spaces.

The general aim of this study was to determine how designers could modify climatic conditions in urban spaces for thermal comfort. Human thermal comfort is "that condition in which a person expresses satisfaction with the thermal environment" *(Fanger 1970)*. It is a subjective response based on both physiological and psychological states of a person in a given environment.

Climatic factors that affect heat exchange with the body are air temperature, humidity, radiation, and air movement. Other factors include the person's activity level, clothing type, and emotional and physical conditions. Previous studies *(Lewis et al. 1971, Vittum 1974)* have shown that air temperatures and relative humidities do not vary significantly throughout the downtown outdoor space system despite differences in physical structures and arrangements. Wind speeds and radiation were much more variable. The designer could therefore modify microclimates in outdoor spaces through control of the wind and radiant environments. This paper focuses on the radiant heat environment.

A person exchanges radiant heat with his surroundings as does any other physical object. Solar radiation always adds heat to a person. The atmosphere and terrestrial objects add or remove heat from a person depending on the temperature difference between the person's outer surface and the surrounding surfaces. If the surroundings are warmer, the person gains heat. If they are cooler, he loses heat.

Several questions were addressed in order to understand the design possibilities for altering radiant-heat exchanges in outdoor spaces. How much radiant heating or cooling is needed for thermal comfort? When is the radiant heating or cooling needed? How much radiant-heat exchange is available to a person in an urban space? A comparison of the

desirable and available radiant-heat exchange quantities revealed design guidelines that could be used for selecting and designing outdoor spaces with comfortable radiant environments.

RADIANT EXCHANGE FOR THERMAL COMFORT

A person must maintain a constant deep body temperature by balancing heat gains and losses with the environment. Thermal conditions that enable a person to maintain heat balance through minor physiological adjustments (a state of thermal neutrality) are the conditions people subjectively select as comfortable *(Bruce 1960, Fanger 1970)*.

Studies with human subjects have shown that radiant heating and cooling can comfortably compensate for cool and warm air temperatures respectively, as long as air movement is low. The radiant environment may be asymmetric about the person as long as nearby ground and vertical surfaces are within comfortable temperature ranges — ground surfaces should be between 17 and 40°C; vertical surfaces should be between 15 and 50°C *(Gagge et al. 1965, Gagge et al. 1967, McNall and Biddison 1970)*.

Determination of Comfortable Ranges of Radiant-Heat Exchange

Fanger's *(1970)* human thermal-comfort model was used in this study to determine radiant-exchange quantities that will yield thermal neutrality depending on other climatic conditions and a person's activity level and clothing type. Fanger's model has been tested extensively with human subjects (in indoor controlled climatic environments) to find the relationship between a person's heat balance and his subjective thermal response.

Although there is no single thermal environment that can satisfy all persons, there are ranges of conditions that are comfortable to a majority of people. Fanger tested his thermal-comfort equation to determine the percentage of people who express dissatisfaction at different thermal sensation conditions, as defined by his model. For the purpose of this study, I selected the range of thermal responses that were found to satisfy more than 50 percent of the people. This includes thermal sensations from slightly cool to slightly warm. The ranges of comfortable radiant-exchange quantities calculated from Fanger's model should be applicable to all healthy persons regardless of age, sex, geographic location, or body size, as long as differences in clothing habits are recognized *(Fanger 1970, Rohles and Johnson 1972)*.

QUANTITIES OF RADIANT EXCHANGE IN OUTDOOR URBAN SPACES

Three sources of radiant heat exchange, exclusive of artificial radiant heat, are available to persons in outdoor environments:

1. Solar radiation: the direct beam, the diffuse radiation from the atmosphere, and reflected radiation from the ground and the vertical surfaces.
2. Longwave radiant exchange with the sky.
3. Longwave radiant exchange with terrestrial surfaces (ground, vertical, and overhead surfaces).

Determination of Radiant-Exchange Quantities

Many environmental factors and a person's physical factors affect the amounts of radiant heat exchanged with a person from these three sources. For this reason, radiant quantities were determined for some specific conditions for persons located in a city in the northeastern United States. Syracuse, N.Y., was chosen for convenience. Conditions were chosen for times when people are most apt to be using outdoor spaces and for typical urban street configurations and surface materials.

A sample of quantitative estimates of a person's net radiant exchange with

each of the three sources was calculated. Solar radiant quantities were calculated by using the equations in Terjung and Louie *(1971)*. Fanger's *(1970)* information on the radiant geometry of a person was used to determine solar radiant quantities absorbed by a person. Solar radiation on cloudy days was computed from Ångstrom's equation as given in Gates *(1962)*. Calculations of net radiant exchanges with the sky and terrestrial surfaces were made with a modified radiation law as described in Plumley *(1975)*. Sky temperatures were derived from Brunt's table of atmospheric radiation in Brown *(1973)*. Terrestrial surface temperatures of typical urban materials were measured in Syracuse during different climatic conditions. The information on a person's radiant area in view of surrounding flat surfaces was taken from Fanger *(1970)*.

Tables of radiant exchanges for the following conditions are presented in Plumley *(1975)*:

1. Solar radiation absorbed by a person on clear days for four different body postures.
2. Total solar radiation absorbed by a person on clear days in the shade of a building, a thin-canopy tree, and a dense-canopy tree.
3. Solar radiation reflected by a glass wall and absorbed by a person.
4. Total solar radiation absorbed by a person on totally overcast days (altostratus and stratus clouds).
5. Net longwave radiant exchange under clear and cloudy skies during different air temperatures (for a person in three typical urban street configurations).
6. Net longwave radiant exchange with typical urban ground and vertical surface materials, shaded and unshaded, at four different times of the day for four air temperature conditions (cool, moderately warm, warm, and hot) typical of the spring, summer, and fall seasons in the northeastern United States.

Summary of Analysis of Radiant Exchange Quantities

Net radiant exchanges of less than 20 to 30 kcal/hr/person were considered to be insignificant because this small amount does not produce a change in a person's thermal-sensation level, as based on an analysis of Fanger's model *(Plumley 1975)*. Therefore, physical factors in the environment that showed insignificant differences in the radiant-exchange quantities for a person were considered to be unimportant for the design of urban spaces.

Some of the results of an analysis of the radiant quantities are presented here, as taken from Plumley *(1975)*:

Solar radiation

1. Direct solar radiation provides much more radiant heat to a person than any of the terrestrial surfaces. Even on cloudy days at noon, diffuse solar radiation can provide 5 to 10 times more radiant heat than terrestrial surfaces.
2. Differences in ground-surface reflectivities (in the range of 20 to 40 percent) are not important during morning or late afternoon. During the midday, higher-albedo materials significantly increase the amount of solar radiation incident on a person. The albedo of shaded ground surfaces is unimportant.
3. Solar radiation reflected from a typical large tinted-glass office window does not provide significant amounts of heat to people.
4. To maximize the solar radiation available to a sitting person (for cool days) seats should be positioned to face the sun, and the ground material should be moderately reflective (like light brick or concrete).
5. To minimize the solar radiation a person receives (on warm days) shade from trees with dense canopies should be provided. Trees with thin canopies, like honeylocusts *(Gleditsia*

Figure 1.—Solar radiation absorbed by a person in the open and in the shade of trees with dense and thin canopies.

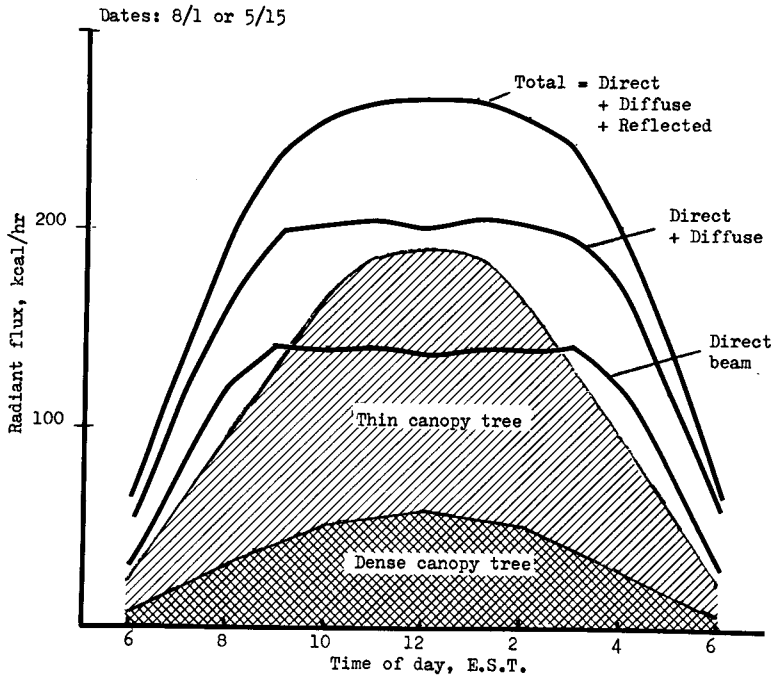


Table 1.—Effect of radiant exchange for a person on an urban street under clear and cloudy skies

Condition	Activity			Effect
	Sitting	Walking slowly	Walking quickly	
Clear skies.....	< 85°F.	< 75°F.	< 60°F.	Cooling
	upper 80s to 99°F.	upper 70s to 99°F.	upper 60s to 90°F.	Neutral
	—	—	> 95°F.	Heating
Cloudy skies.....	< 65°F.	< 55°F.	—	Cooling
	upper 60s to 95°F.	upper 50s to 85°F.	40° to 75°F.	Neutral
	> 95°F.	> 85°F.	> 75°F.	Heating

Note: The air temperatures considered here are for the range from 30 to 99°F. The clothing types used for this table were those typically worn during the different air temperatures.

triacanthos), are not as effective for shading as dense-canopy trees (fig 1).

Radiant Heat Exchange with the Sky

1. The sky can be a source of radiant cooling or heating depending on the air temperature and cloudiness. During warm weather the clear sky can have a cooling effect only for seated persons or slow walkers (table 1).
2. In cool weather radiant cooling is undesirable, and spaces should provide overhead obstructions to those portions of the sky not in the direction of the sun.
3. In warm weather radiant cooling is

desirable. Spaces for sitting should not be located directly under overhead canopies and should preferably be located away from building walls in order to maximize the sky view.

Radiant Heat Exchange with Terrestrial Surfaces

1. Ground and vertical surfaces can be sources of radiant heating or cooling depending on their surface temperatures, surface dimensions, proximity to the person, and the person's activity level. Graphs were constructed to show a person's radiant exchanges with ground and vertical surfaces, each of dimensions large enough to provide the near maximum exchange (figs. 2 and 3). Surface dimensions larger than these do not significantly increase the radiant exchange for a person. This was determined from an analysis of Fanger's *(1970)* view factors between a person and ground and vertical surfaces.
2. Ground surfaces generally provide more radiant exchange than either vertical surfaces (walls) or overhead surfaces (trees or awnings). The latter usually provide negligible quantities of net radiant exchange.
3. The surface areas of ground or vertical surfaces need not be very large to provide significant amounts of radiant exchange. On warm days unshaded ground surfaces as small as 4 square meters or vertical surfaces 14 meters long and 4 meters high can provide undesirable amounts of radiant heat to a person.
4. Radiant exchange with vertical surfaces becomes insignificant for persons located more than 3 meters from the surface. (This applies to walls, 10 meters high and 14 meters long, with surface temperatures between 10 and 40°C—typical of the extremes found in the summer and fall seasons in Syracuse.
5. During warm weather, shaded ground surfaces offer significantly less radiant heat to persons than unshaded surfaces, with the exception of vegetative ground materials (fig. 4).
6. Walls shaded by dense-foliage trees offer significantly less radiant heat to persons than unshaded walls. Walls shaded by vines or shrubs did not show significantly lower surface temperatures than the unshaded portions, and differences in net radiant exchange with persons were negligible.

DESIGN GUIDELINES

Comparisons of available radiant exchanges were made for: (1) conditions providing the maximum amount of radiant heat gain, and (2) conditions providing the least amount of radiant heat gain (or most radiant heat loss) from each of the three radiant-exchange sources. An example of these comparisons is presented for a seated person at noontime on a warm day (fig. 5).

Comparisons of radiant heat exchange for thermal comfort and radiant exchange available to persons revealed some simple design guidelines (figs. 6 and 7). Four elements, as indicated on the charts, should be considered in the design of a space depending on the air temperature conditions, time of day, and the person's activities:

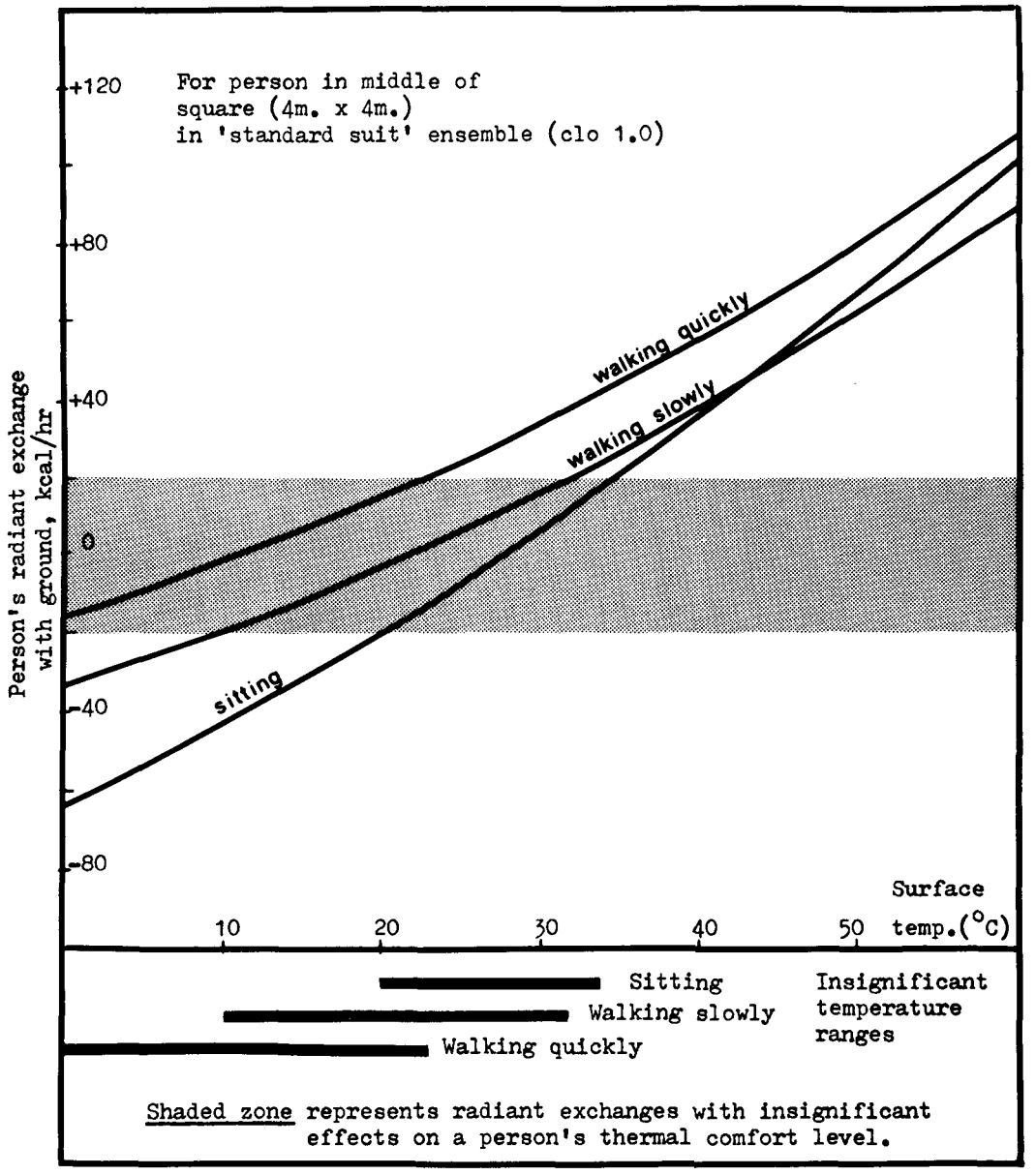
1. Direct solar radiation should either be available or should be shaded by thin or dense-canopy trees.
2. Ground and vertical terrestrial surfaces should be shaded or unshaded.
3. Sky views overhead and to the sides of persons should be either blocked or made as large as possible.
4. Wind speeds should be either calm, low (1 to 3 mph), or moderate (4 to 5 mph).

Footnotes accompanying the charts provide additional specifications for some of the categories.

Artificial Radiant Sources

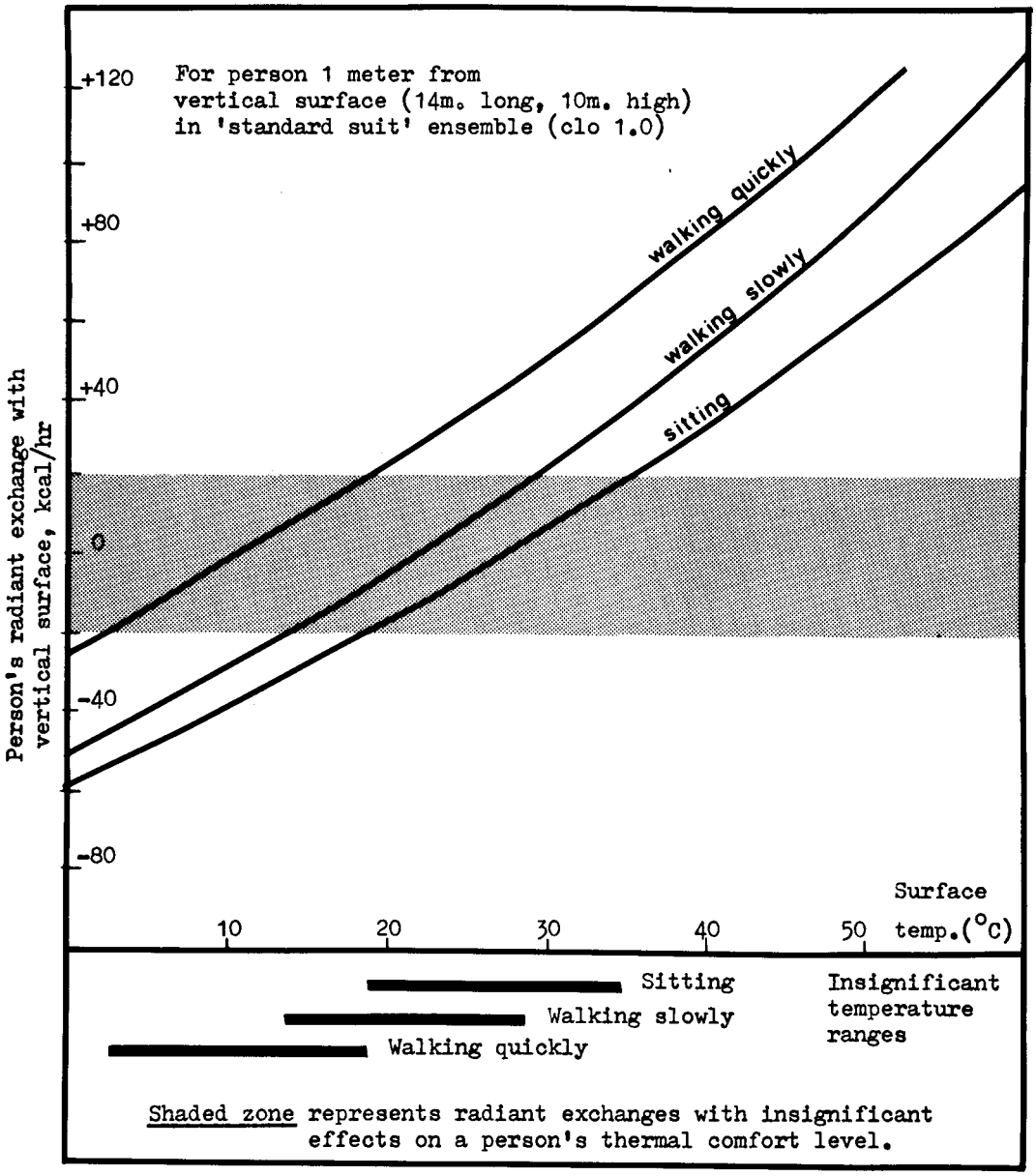
Spaces can be designed to include artificially-warmed ground and vertical

Figure 2.—Effect of ground-surface temperature on radiant exchange between a person and the ground.



Note: If clo 0.5, subtract 15 kcal/hr from radiant flux.
If clo 1.5, add 15 kcal/hr to radiant flux.

Figure 3.—Effect of surface temperature of a vertical surface on radiant exchange between a person and the vertical surface.



Note: If clo 0.5, subtract 20 kcal/hr from radiant flux.
If clo 1.5, add 20 kcal/hr to radiant flux.

Figure 4.—Person's radiant exchange with shaded and unshaded ground surfaces on a clear warm day.

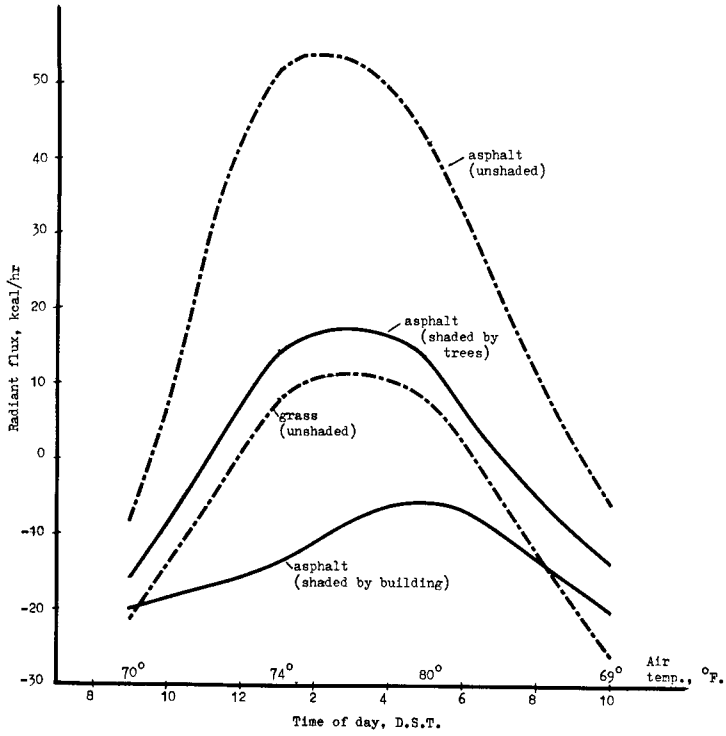
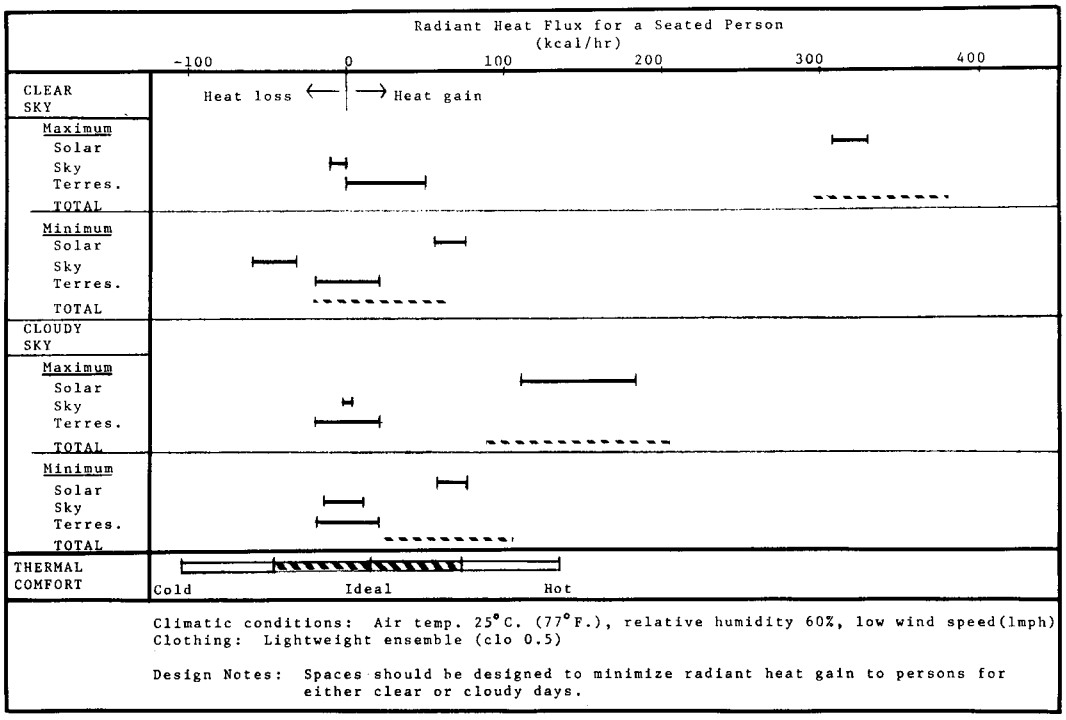


Figure 5.—Comparison of desirable and available radiant exchanges.

WARM DAY - NOONTIME



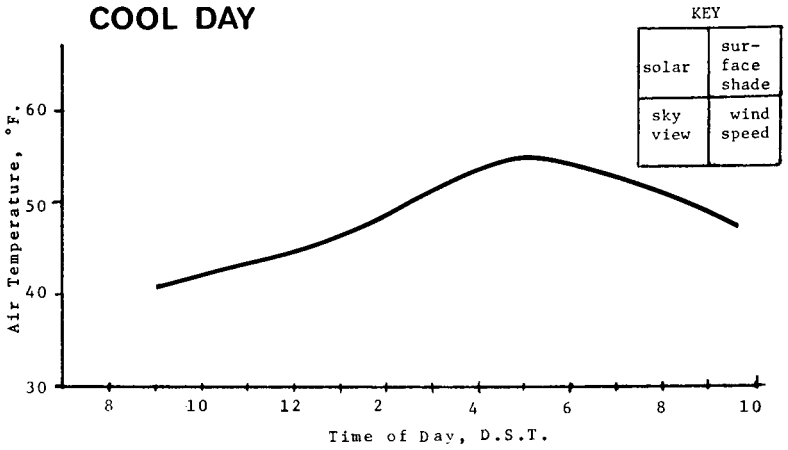
Climatic conditions: Air temp. 25°C. (77°F.), relative humidity 60%, low wind speed(1mph)
Clothing: Lightweight ensemble (clo 0.5)

Design Notes: Spaces should be designed to minimize radiant heat gain to persons for either clear or cloudy days.

Figure 6.—Design guideline chart for clear cool days.

Where the design elements are not sufficient to provide thermal comfort, the relative degree of discomfort is indicated below the activity/time of day category.

1. If ground and vertical surfaces can be artificially warmed to 40 and 50°C, respectively, a person seated near a wall in a space with a small sky view can receive enough radiant heat to feel only slightly cool.
2. If a person has a large sky view, solar radiation should be maximized (seats facing the sun and ground materials that are moderately reflective to the sun).
3. Solar radiation available to the person should be maximized. Vertical surfaces should not be near the person unless they are heated.
4. The best place on a street for a person to walk would be away from vertical walls, but on the side of the street. A row of trees between the person and the buildings can reduce the sky view.
5. If the sky view is small, a person should be over a low reflective ground material.
6. Hard, dense materials (not vegetation or wood) should be used for the ground surface. Heated ground and vertical surfaces could provide enough radiant heat for thermal comfort.
7. Ground surfaces may be shaded or unshaded. Walls facing the sun should be shaded. A person will not be cooled by wind unless he has been perspiring.



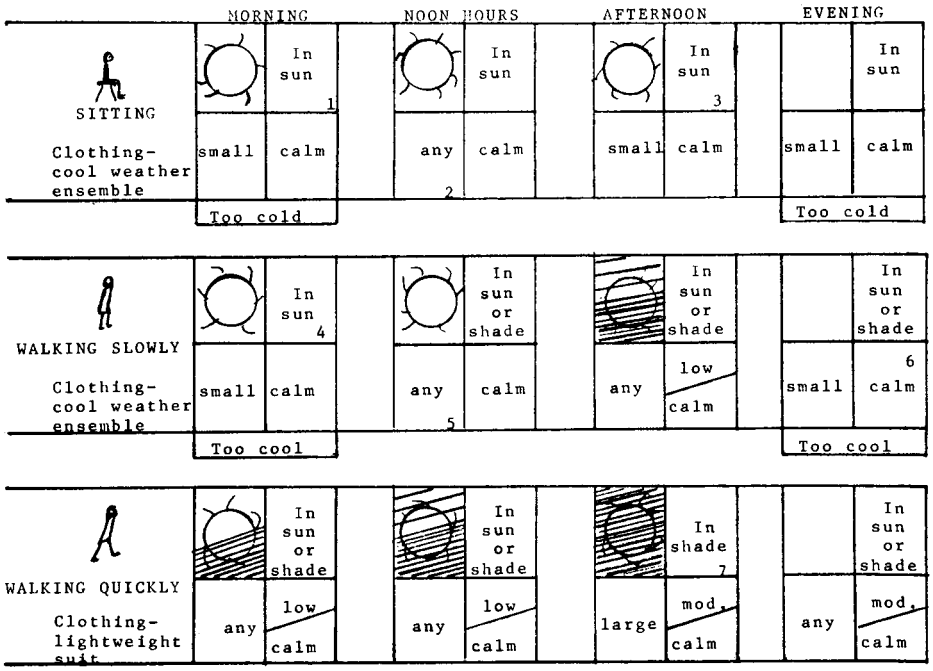
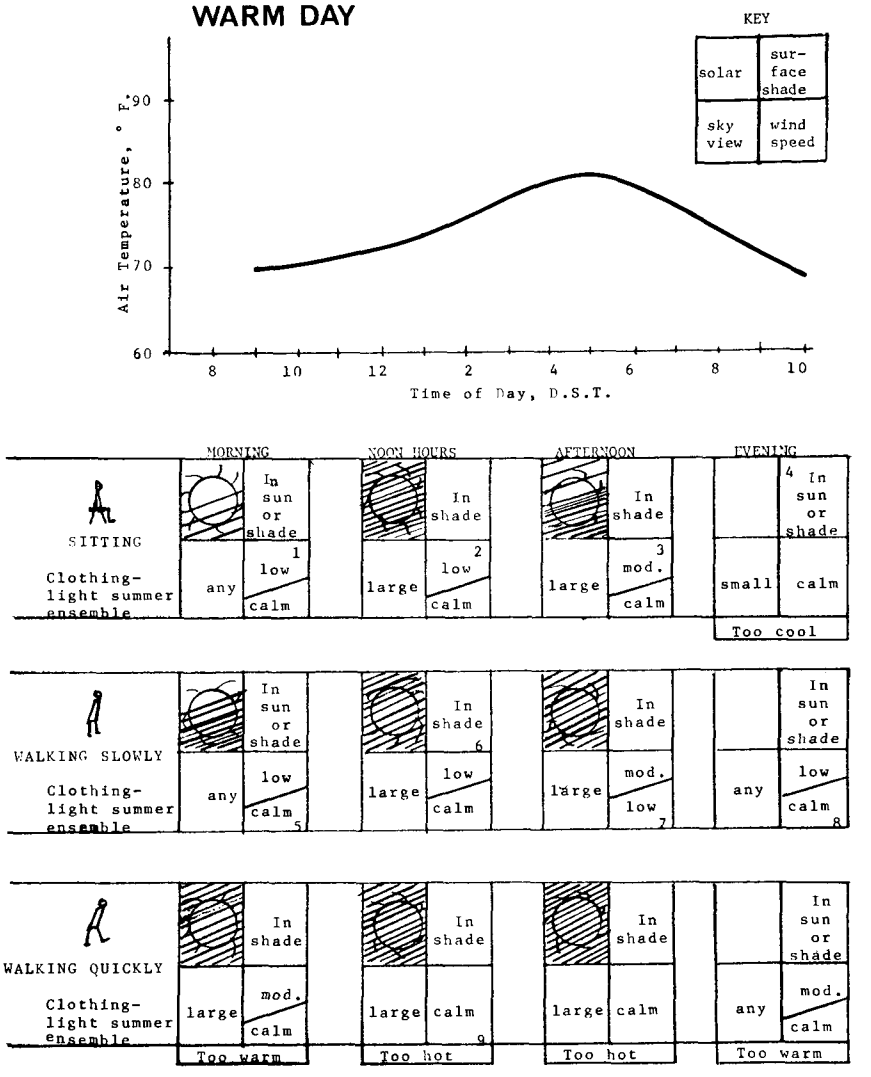


Figure 7.—Design guideline chart for clear warm days.

Where the design elements are not sufficient to provide thermal comfort, the relative degree of discomfort is indicated below the activity/time of day category.

1. If direct sun is desired, a breeze is necessary and a reduced sky view is desirable.
2. Unshaded vegetative ground surfaces and unshaded vertical surfaces are acceptable. If direct sun is desired, artificially cooled ground and vertical surfaces (for example, a water wall) with surface temperatures of at most 17 and 15°C, respectively, can provide enough radiant cooling for a person to feel only slightly warm.
3. Unshaded vegetative ground surfaces are acceptable. Light shade from solar radiation can be comfortable if the space is breezy and the person is in light summer clothing.
4. Artificially warmed ground and vertical surfaces can provide enough radiant heat to compensate for the cool air temperatures even under slightly breezy conditions.
5. If direct sun is desired, a breeze and a larger sky view are necessary. Dense tree shade is comfortable unless the space is windy and a person is dressed in light summer clothing.
6. Unshaded vegetative surfaces can be used. Persons in medium weight suit ensembles may be too warm despite these microclimatic considerations.
7. A person in medium-weight suit ensemble will be too warm.
8. If the space is breezy, it is important to minimize the sky view for a person in light summer clothing.
9. Air movement across a person will add heat to him unless he is wet with perspiration.



surfaces (for example, cooled water walls) for warm weather. Seated persons can be comfortable during noon hours at 0°C in spaces that provide the cool weather needs (fig. 6) plus ground and vertical surfaces of 40 and 50°C respectively. Spaces designed for warm-weather needs (fig. 7) can be fairly comfortable for seated persons at 31°C if cooled ground and vertical surfaces of 17 and 15°C respectively can be included.

Limitations of the Design Guidelines

These design guidelines should be applicable to cities with latitudes and climatic conditions similar to Syracuse. They are based on the thermal-comfort needs of the average healthy person who has equilibrated to the outside thermal environment. They do not take into account the special thermal desires of particular groups of people; for example, office workers coming from cool air-conditioned buildings seeking sunshine for warmth, or a tan or perspiring construction workers in need of a cool breezy space.

Outdoor spaces offering a variety of radiant environments may best satisfy a majority of the people. However, the radiant environments indicated in the design guidelines should be among the available options.

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Acknowledgments. The author thanks Lee P. Herrington, who assisted in all technical aspects of this project.

Topoclimatic Aspects of Developmental Suitability in the Metropolitan Landscape

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ABSTRACT. — A computer-based procedure for geographically identifying rating, and ranking topoclimatic characteristics is described. The influences of topography, land use, and soils are considered and combined into a single composite topoclimate developmental suitability map drawn by a Cal Comp plotter. By allocating development to the most suitable topoclimate areas, the long-term energy costs of maintaining human health and comfort could be minimized.

THE GROWTH OF METROPOLITAN REGIONS in North America has not profited from the potential topoclimatic benefits offered by the natural landscape. With the increasing concern for conservation of our energy resources, the long-term costs of ignoring the potential benefits of locating developments, in the most suitable topoclimates becomes inexcusable. Basic principles of applied climatology should be integrated into the physical, social, and economic principles of landscape planning to increase human health and comfort at least cost.

At the University of Massachusetts an interdisciplinary planning research group, operating under the acronym METLAND (Metropolitan Landscape Planning Model), has been working on a system of integrated, computer-based landscape-assessment procedures *(Fabos 1973)*.

The METLAND model is composed of three major assessment procedures, defined as components. The first component identifies and evaluates special-value resources such as prime agricultural lands. The second component identifies and evaluates hazards such as high noise-pollution areas. Together, the special-value resource and hazard components identify and evaluate environmental constraints to development. The third component is the developmental-suitability component, which strives to identify and evaluate those landscape parcels possessing positive intrinsic attributes that offer maximum benefits and least cost to the resident, community, and developer.

Within the developmental-suitability component there are three variables which are assessed. These are physical (slope, depth to bedrock, etc.) visual (land-use compatibility) and topoclimatic. By assessing the physical, visual, and topoclimatic attributes of the landscape, the most intrinsically suitable areas for development may be identified, rated, and ranked. The purpose of this paper is to report on the initial pro-

cedure and results of the topoclimate developmental suitability variable of the METLAND model.

The goal of the topoclimatic assessment research was to design and implement a procedure, using established principles of applied climatology, to assess the topoclimatic suitability within a town or region for various development and planning purposes. A review of current literature was made to clarify and define the characteristics of optimum topoclimatic areas that would be most suitable for development. It was found that the most suitable topoclimatic areas would support metropolitan growth that minimizes long-term costs of maintenance over the short-term costs of development. Specifically, we should aim for long-range stability through low energy maintenance demands for artificial heating and cooling of the built environment *(Knowles 1974)*.

In addition to energy savings, we should also strive for maximizing human comfort, safety and health by taking full advantage of natural topoclimatic opportunities and minimizing regional or mesoclimatic stresses *(Mather 1974)*.

In the terminology of Olgyay *(1963)*, the most important topoclimatic objective for the New England region is to minimize underheated areas. By locating development to maximize exposure to winter solar receipts and to minimize the effects of winter winds, underheated areas can be avoided. Areas susceptible to overheating should also be avoided, although these are less significant in the New England region.

A final objective to be considered concerns fog, frost, and excessive moisture. Frequent fogs and high humidity enhance the danger of moisture damage to building materials and paint. Critchfield *(1966)* reports that, where air pollution is common, the chemical effects of moisture damage is much greater when associated with dirty fog particles.

Our task required the translation of these objectives into landscape subvariables which could be measured and used to interpret probable topoclimatic conditions within a region.

METHODOLOGY

Selection of Subvariables

Recorded climatic data for assessing towns of 10 to 40 square miles or regions of hundreds of square miles are scarce because the number of recording stations is limited. Consequently, variations in local topoclimate must be derived indirectly. Interpreting topoclimate from variations in topography (slope, orientation, elevation) has received considerable attention. The early works of Geiger *(1965)* and Olgyay *(1963)* provide much of the basis for interpreting local climatic conditions resulting from variations in topography.

Another important influence on topoclimate is land use, reflecting various heat-capacity and heat-conductivity capabilities. Nicholas *(1971)*, Landsberg *(1969)*, and Mitchell *(1962)* have reported on the temperature differences over different surfaces resulting in urban heat islands. These are characteristic of most North American cities for at least part of the year. Even in the new town of Columbia, Maryland, where efforts to reduce the heat-island effect have been made, a measurable heat island has already been detected by Landsberg *(1969)*. Surface temperature values measured from a helicopter, using infrared instrumentation over Columbia on a sunny morning, recorded differences of up to 8.5°C between forested and builtup areas.

Together, the influence of topography and land use were thus recognized as major contributors to topoclimatic differences within our study area. The problem was to determine which specific subvariables of topography and land use had the greatest effect on overheating, underheating, and moisture. In addition, these subvariables had to be meas-

urable from existing and easily available data sources.

Topography.—The subvariables of topography having major effects on topoclimate are slope, aspect, and elevation with respect to sun and wind. The relative differences of sun and wind in turn have major impacts on overheating and underheating.

Effects of topography on wind can be of an active or passive nature. For example, an active topographic influence results from differences of air temperature and pressure, which causes cool air to flow down slopes. This phenomenon is known as katabatic wind. Passive effects of topography on wind are demonstrated by the behavior of an airstream over or around an obstacle.

In New England, exposure to strong northerly winter winds increases convective cooling. By avoiding windward slopes, summits, and large unprotected open spaces, convective cooling can be minimized. Topographic features such as low-lying or basin areas surrounded by higher elevations should also be avoided because they induce drainage of cool air, which is a prime cause of frost and fog formation *(Critchfield 1966)*.

Topography has a major influence on the total solar radiation (insolation) that a site receives. The amount of solar radiation received by a surface is determined by: (1) compass orientation, which determines the number of hours of sunshine received and the time of day when it is received; (2) the slope of the surface, which determines the amount of energy received per unit area; (3) the shadowing effect of adjacent relief, which blocks out portions of direct sunshine during the day; and (4) the relative elevation of the surface above sea level, which reflects the reduction of atmospheric absorption of incoming radiation.

Significant differences in solar radiation receipts resulting from topography have long been recognized, particularly in agriculture. Benefits from reduced heating costs to homeowners and industry can be achieved by locating developments where maximum amounts of solar radiation are available during underheated periods *(Olgyay 1963)*.

Calculating the distribution of solar radiation has been accomplished by using a computer program developed by Williams and others *(1972)*. Data input requirements are a grid of elevations, the solar declination, latitude, transmissivity, and day of the year. Direct, diffuse, and total global radiation can be calculated, as well as absorbed radiation if albedos are specified at the grid points. A contour map is produced by using the Harvard SYMAP program or a similar contouring program that geographically locates the distribution of solar radiation.

Moderating effects of land use. — Grass, pavement, soil, or trees, differ widely in their ability to conduct and store heat. Forests and buildings also have significant effects on local winds. Some surfaces, such as forest canopies, tend to moderate topoclimatic stresses by minimizing extremes. Natural opportunities to control extreme wind velocities and temperatures should be taken advantage of wherever possible.

Recognition and use of moderating factors is included in our assessment by differentiating between various land uses. Forests or even a few rows of trees will greatly reduce wind speed. Based on 10 years of wind records at a height of 4.6 m inside and outside a maple-beech-birch forest, the wind speed in the forest was less than 50 percent of the speed outside for 11 months of the year *(Zon 1941)*. In fact the reduction of winds by 50 percent reduced residential heating requirements by 30 percent. Critchfield *(1966)* noted that the major climatic effect of trees is roughly proportional to the density of the forest cover, but forest can modify the climate of adjacent areas as well. Generally it is assumed that the downwind zone of

protection from winds offered by trees is equal to 20 times the height of the tree barrier.

In the model, two categories of forest are identified to reflect their moderating climatic effects: (1) forests with a crown density greater than 80 percent and a height greater than 41 feet, and (2) forests with a crown density between 30 and 80 percent and height between 20 and 41 feet. Although it was recognized that a greater differentiation of forests into hardwood and softwood categories would improve the accuracy of the assessment, we believed two forest categories were sufficient for metropolitan planning purposes.

Nonforested areas are divided into two other categories to reflect differences in their heat absorptivity and conductivity: (1) densely urbanized areas with large amounts of paving, which increase the stress of overheating, and (2) remaining open lands believed to have little moderating or stress-increasing effects on topoclimate.

Numerous other subvariables were investigated, but were not incorporated into our assessment chiefly because we wanted to keep the procedure as simple as possible and still provide sufficiently accurate information to aid those making planning decisions. The influence of major water bodies and extreme differences in elevation are special instances where new subvariables would be required. Other topoclimatic conditions, especially those relating to city climates and air pollution, were not considered in the procedure.

Procedural-framework

Although space does not permit us to go into sufficient detail to explain the intricacies of the assessment procedure, we can provide a general overview. The procedure can be organized into three basic steps.

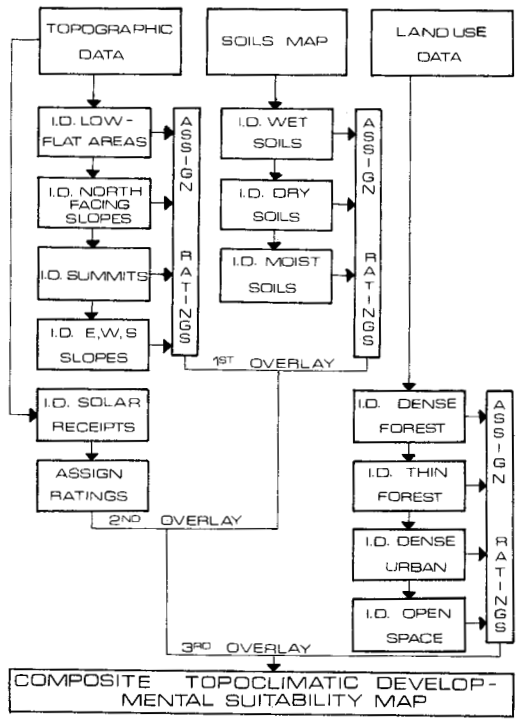
1. Data collection.—Topographic data may be obtained manually from USGS topographic maps or directly from magnetic tape available from the USGS National Cartographic Center at Reston, Va. Land-use data may be obtained from interpreted aerial photographs and soils data from detailed SCS soil maps.

2. Source-map preparation. — The second step is really a two-stage procedure. Once the data have been collected, they must be put into a mapped format, which is then digitized and stored on magnetic tape. Using the COMLUP computer mapping system, as described by Ferris and Fabos *(1974)*, and the assessment procedure presented here, a series of source maps are then produced.

3. Overlay procedure.—The third and final step produces a series of composite overlay maps culminating in a composite topoclimatic developmental-suitability map. Again, the computer is used to overlay the maps.

A procedural flow chart (fig. 1) shows the assessment process from data ac-

Figure 1.—Topoclimate developmental suitability assessment procedure.



quisition to the final topoclimate suitability assessment map. Preparation of each source map and the overlay procedure will be briefly described next.

Source-Map Preparation

The topoclimate developmental-suitability-assessment map is generated from four source maps: (1) a topograhic map, (2) a land-use map, (3) a soils map, and (4) a solar-radiation receipt map. Source map information is digitized into computer manipulatable format so that overlays or composite assessments and evaluations can be made.

The following discussion briefly outlines the general procedures for preparing each source map, using the town of Burlington, Massachusetts, for demonstration purposes.

Topographic source map. — Using topographic data from one of the previously identified sources, we identified low-lying, relatively flat areas, summit areas, north-facing slopes, and remaining areas of south, west, and east slopes. These areas may be identified by interpreting 10- or 20-foot contours or with computer assistance using a 200- or 500-foot grid network. Low-lying, relatively flat areas are given a 1_f rating because potential fog and frost conditions may exist in these areas. Summits are given a value of 1_s because potential high wind conditions may be expected in these areas. North-facing slopes are given a value of 1_n because this orientation to winter winds is least suitable for comfort and heating in cold temperate climates. All other areas are assigned a rating of 2, which reflects their minimum influence on topoclimate; the higher ratings indicating the most desirable areas for development.

Land-use source map.—Land use can have a significant effect on local topoclimate. These differences are reflected in the following land-use aggregations. All urban/commercial/industrial uses are given a 1_u value because of their potential for overheating in summer. Forested areas are recognized for their moderating effect on climate in both winter and summer by assigning a value of 3 to those areas having a crown density between 30 and 80 percent and a height of 21 to 41 feet. A value of 4 is given to forests with a crown density greater than 80 percent and height greater than 41 feet. Remaining open space and crop and pasture lands are considered to have no significant moderating effect and are given a value of 2.

Soils source map.—The tendency of moist soils to remain cooler during the day and warmer during the night is included in the assessment by giving moist soils (soils with moderate to slow percolation) a value of 2 and dry soils (soils with excessive percolation) a value of 1_d. Soils with a seasonally high water table or very poorly drained soils are given a value of 1_w. These wet soils, in combination with relatively low-lying and flat areas, are susceptible to fog and frost in relation to other areas.

Solar radiation source map. — The radiation source map depicts the distribution of global radiation for a given period and transmissivity over an area at a given latitude, the topography of which is specified. Areas of high, medium, and low global radiation are given values of 3, 2, and 1_r respectively for winter since maximum radiation is needed at this time. For our study areas a maximum difference of 98 langleys per day between areas for 21 December were obtained, assuming a sunny day. This range was divided into three categories of 0 to 30, 31 to 60, and 61 to 98 to reflect the relative contribution of solar receipts during underheated periods.

During the summer a minimum of solar radiation is needed. If desired, the high, medium, and low areas of summer solar receipts can be given values of 1_{sr}, 2, and 3 respectively.

In some regions of little topographic variety, the difference in solar receipts is relatively insignificant (less than 30

langleys per day). In other cases the differences in solar receipts are so large that the solar-radiation values become the major contribution to topoclimate differences.

Composite Overlay Preparation

First, the topographic source map is overlaid with the soils source map. Areas possessing a high water table or poorly drained and low-lying and flat are susceptible to fog and frost.

The topographic and soils source map is next overlaid with the solar-radiation source map. Potentially overheated and underheated areas can now be identified. Overheated areas will be identified by combinations of maximum summer solar receipts and dry soils. Underheated areas will be areas of minimum winter solar receipts, dry soils, and exposure to cold winter winds along ridges and north-facing slopes.

Finally the land-use source map is overlaid with the series to produce a final composite topoclimate suitability map. The land-use source map reflects the effect forests and heavily builtup areas have on topoclimate. The moderating effect of a forest improves both a potentially overheated area as well as an underheated area. Surfaces that are paved and highly urbanized exacerbate the overheating problem:

In summary, the following subvariables are identified and rated:

Topographic	*Rating*	*Land use*	*Rating*
North slope	1_n	Urban	1_u
Summit	1_s	Open rural	2
Low & flat	1_f	Forest (thin)	3
E,W,S slopes	2	Forest (dense)	4

Solar	*Rating*	*Soils*	*Rating*
Low	1_r	Dry	1_d
Medium	2	Wet	1_w
High	3	Moist	2

After all four maps have been overlaid, the total range of values for an area with little topography is from 4 to 9. This condition results when there is no significant effect of topography on solar receipts, and the entire study area receives a single value of 1. However, in an area with significant topography, the composite value range is from 4 to 11. Both value ranges are divided into three suitability categories to reflect a hierarchy of suitability: (A) most suitable, (B) marginally suitable, and (C) least suitable.

For an area with little topography, the influences of land use (such as forests) and of soils become dominant, resulting in the following suitability categories:

8 to 9 — most suitable (A)
6 to 7 — marginally suitable (B)
4 to 5 — least suitable (C)

For an area with significant topography (when the solar ratings are from 1 to 3), the suitability categories are:

9 to 11 — (A)
6 to 8 — (B)
4 to 5 — (C)

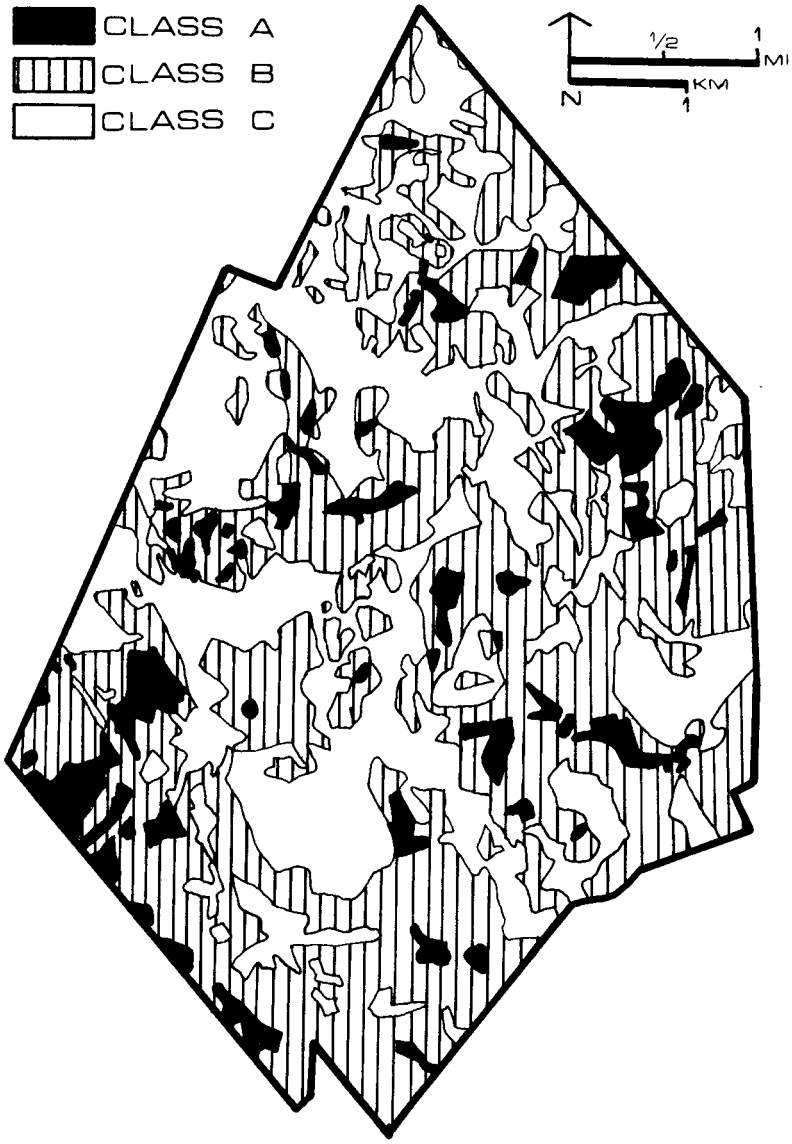
For the Burlington area (in 1971) 9 percent of the area was given a rating of A, 52 percent a rating of B and 39 percent a rating of C. Further work on identifying which suitability categories have been most intensively developed since 1952 is presently under way.

RESULTS

The composite topoclimate suitability map (fig. 2) shows the distribution of topoclimates in Burlington, Massachusetts. Topoclimate differences in Burlington are minimal primarily because there is little topographic change within the town. Most of the topoclimate differences result from the distribution of land-use types. Dense forest areas contrast sharply with the extensively built-up areas along Route 128.

In addition to mapped output, tabular information on each parcel is also available. This information is extremely important because it provides an account-

Figure 2.—Topoclimate developmental suitability map, Burlington 1971.



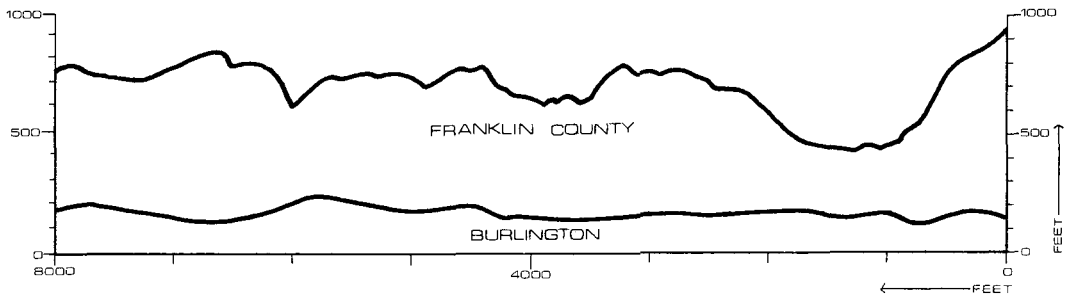
ing of the various values received by the parcel. For example, a developer has submitted a subdivision plan to Burlington in a C-rated area and wishes to know why the town fathers tell him that the site is topoclimatically least suitable. The developer may then be shown a map and a print-out with the following information:

Parcel No.	*Topo*	*Land use*
18	1_n	2

Soils	*Solar*	*Total*	*Rating*
1_d	1_r	5	C

From this information, both the town and the developer know that the site is on a north-facing slope, in a rural open non-forested area with dry soils and a

Figure 3.—Topographic cross-sections of Burlington and a portion of Franklin Co., Massachusetts.



minimum amount of solar radiation receipts in winter. Such information indicates increased heating costs and a reduced outdoor comfort season to the potential homeowners; increased costs to the town for winter road maintenance for sand, salt, and snow removal; and increased costs to the developer through a reduced construction season.

The significance of topographic change to topoclimate can be seen between two areas in Massachusetts. The range in Burlington is from 135 langleys to 170 langleys for the 21 December. For a portion of Franklin County the range is from 100 to 195 langleys under similiar conditions except for topography. A comparison of the topography of the two areas is shown in the topographic cross-sections (fig. 3). It is clear that the greater range in solar radiation receipts in Franklin County is the result of the greater relief in that area.

CONCLUSIONS

The purpose of this paper has been to describe a topoclimate developmental suitability assessment procedure. The procedure has been applied to Burlington, Massachusetts, and partially to an area in Franklin County, Massachusetts. Topoclimatic differences were mapped, using a computer-based mapping system.

Although complete field checks with the mapped assessments have not been completed, preliminary comparisons are encouraging. Instrumentation to measure wind speed and solar radiation is now being set up in Franklin County by the Department of Mechanical and Aerospace Engineering at the University of Massachusetts. These data will be used to test the accuracy of the present procedure and to quantify potential cost savings among identified topoclimates.

The information provided by the procedure will be useful to decision-makers who must make land-use-management decisions. Once areas that minimize the long-term costs of maintenance and maximize the intrinsic capability of the landscape to provide health and comfort have been identified, planning decisions may then anticipate and reflect present and future costs prior to actual development.

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METROPOLITAN ACOUSTIC ENVIRONMENTS AND USE OF VEGETATION IN NOISE CONTROL

Range of Sound Levels in the Outdoor Environment

by LEWIS S. GOODFRIEND, *Lewis S. Goodfriend & Associates, 7 Saddle Road, Cedar Knolls, N. J. 07927.*

ABSTRACT.—Current methods of measuring and rating noise in a metropolitan area are examined, including real-time spectrum analysis and sound-level integration, producing a single-number value representing the noise impact for each hour or each day. Methods of noise rating for metropolitan areas are reviewed, and the various measures from multidimensional rating methods such as the Composite Noise Rating are examined, along with the trend towards single-number rating schemes. The reliability of the various noise-measurement and evaluation methods is discussed in terms of planning needs.

THE RANGE OF OUTDOOR NOISE levels is extremely large, ranging from the tranquil quiet of the wilderness to the noisy urban environment. Some people live within 15 feet of the right-of-way of major highways, where the outdoor noise levels may be above 90 dB(A). Many suburban and suburban rural residents live along the right-of-way of major interstate highways and local freeways where even at 100 or 200 feet the sound levels approach 90 dB(A). A far larger number of people live in the rural, suburban, and urban areas more distant from the transportation systems. They are exposed to what, for most of the residents within each area, are noise environments that are quite acceptable. Even here the sound levels range from below 30 dB(A) to as high as 65 or 70 dB(A).

Some specific examples will show the nature of these noise exposures. In one remote rural farming community, the range of residual ambient sound levels across the entire acoustical frequency spectrum for a 24-hour period remained below 41 decibels (fig. 1 and fig. 2). In this same community, the intrusive or L_{10} A-weighted sound levels, the level below which 90 percent of all levels will occur, was only 43 decibels (fig. 3).

For the suburban rural environment, the residual ambient sound levels still have some indication of the flatness with frequency while the L_{10} sound levels as a function of frequency exhibit the spectrum of vehicular traffic (fig. 4).

In the urban environment, both the residual (L_{90}) and the L_{10} levels as a function of frequency show the concave bulge in the midfrequency range characteristic of road traffic (fig. 5).

Even in the urban environment the top ten percent of the levels must be the ones considered intrusive. The intrusions show up with sound levels reaching peaks as high as 90 dB(A). However, the duration is short for any given intrusion (fig. 6).

It is unfortunate that these noises cannot be described in writing because much is lost in the inability to describe all the dimensions of a sound. How can

Figure 1.—Range of summer-day residual ambient noise levels in a rural farming community.

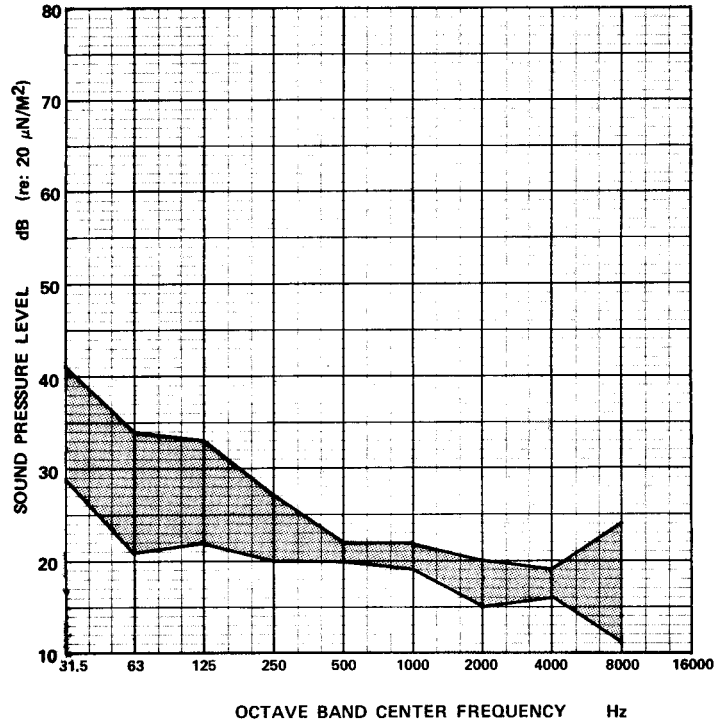


Figure 2.—Range of summer-night residual ambient noise levels in a rural farming community.

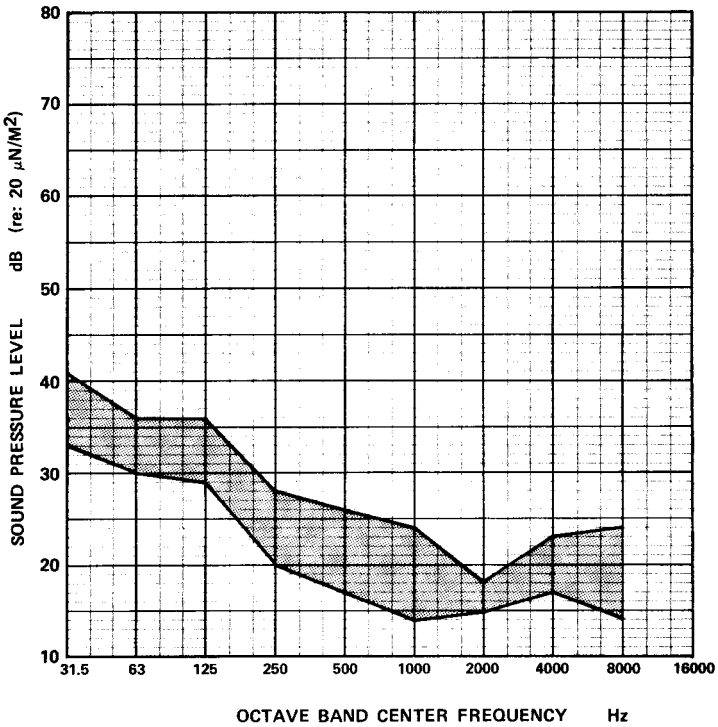


Figure 3.—Statistical distribution of summer-day noise levels in a rural farming community.

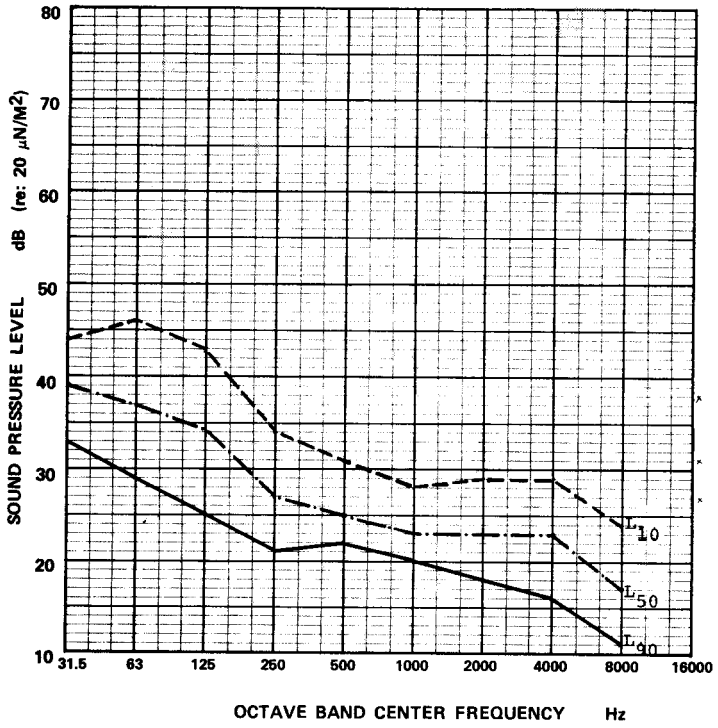


Figure 4.—Statistical distribution of summer-day noise levels in a suburban-rural community.

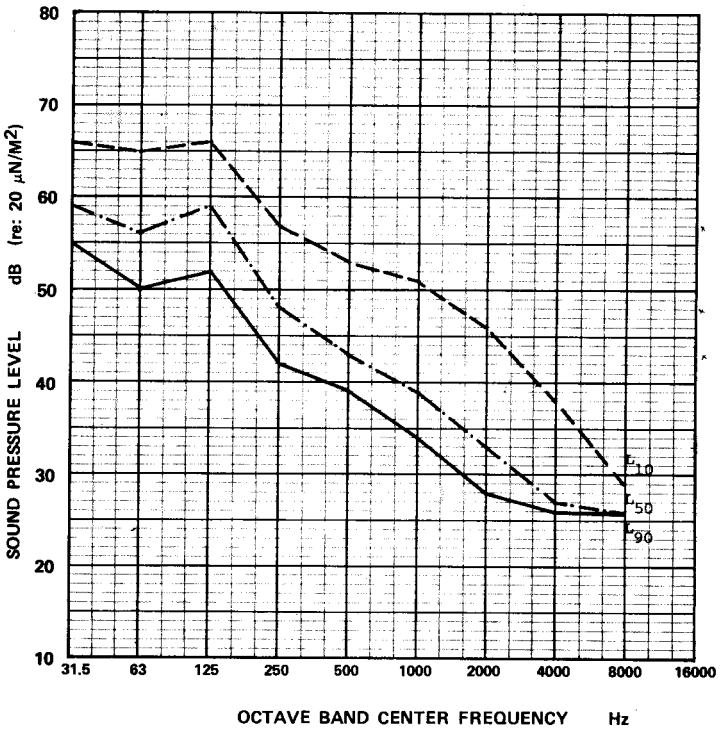


Figure 5.—Statistical distribution of summer-day noise levels in an urban community.

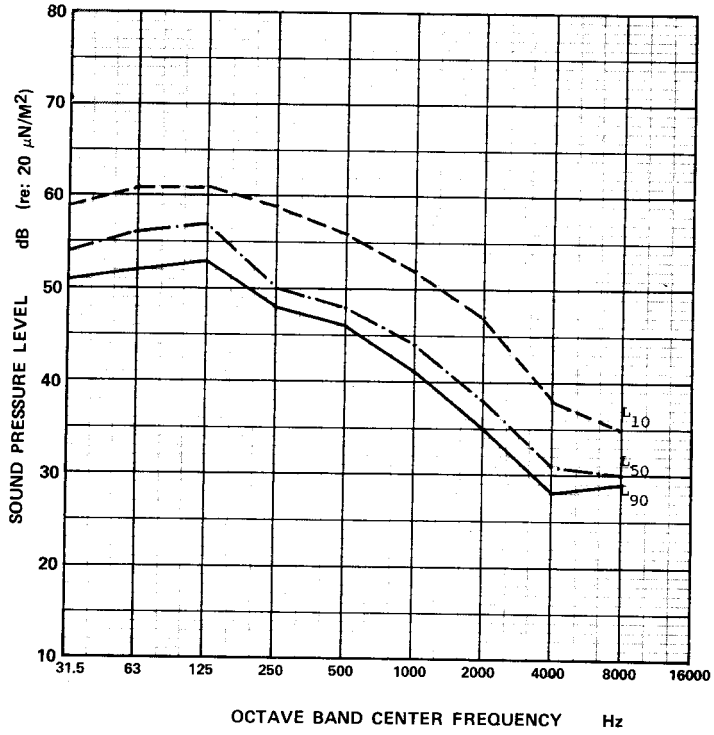
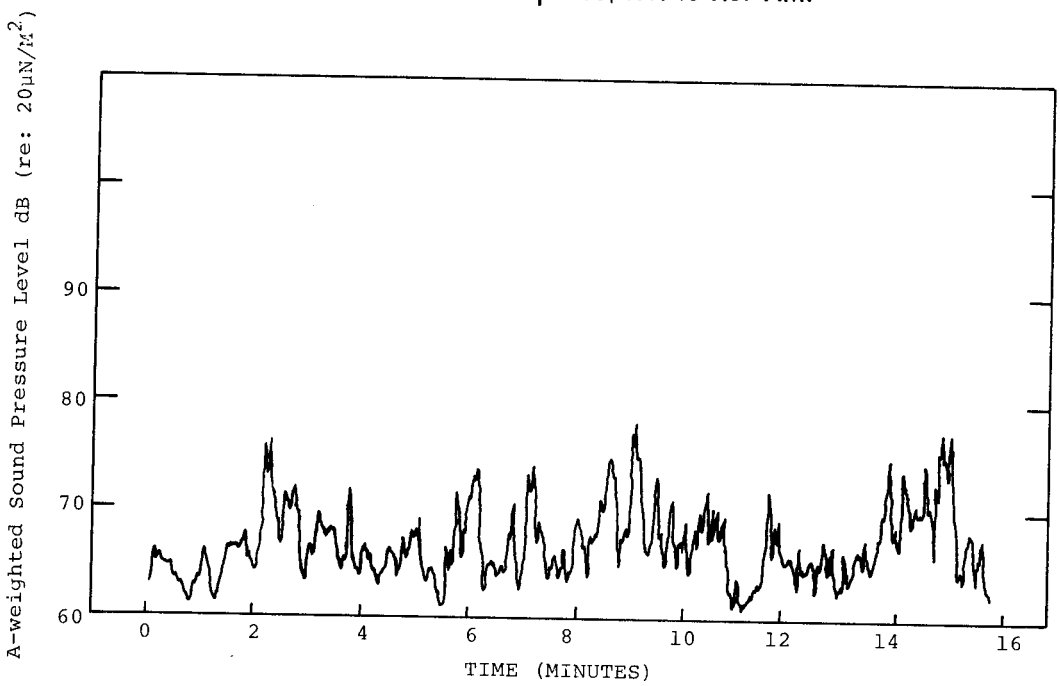


Figure 6.—Time history of the daytime noise levels in a typical urban environment over an 18-minute period, 1:41 to 1:57 P.M.



the pleasant rural summer evening with crickets and peepers producing sound levels in the 40 dB(A) range be compared to the much less acceptable sound of a nearby air conditioner's air-cooled condenser, even though both spectra are rich in high frequency energy. Even more difficult to describe is the difference in the qualities of sounds made by a large heat exchange cooling tower with its water spray and splashing sounds, and the sound of the surf. The acoustical spectra may be quite similar, but one is enjoyed and the other is seldom tolerated, even at sound levels 15 to 20 decibels lower. Of course, one would not exepct to hear the sound of surf pounding the shore in an urban apartment at any sound level. It actually occurs at levels above 60 dB(A) in homes along the shore line in many beachfront communities.

There are many other groups of sounds having similar spectra and levels that range from the totally unacceptable to the pleasurable. It is clear from much of the research on the effects of noise on man that context and associative factors play major roles in the acceptability of sounds that do not interfere with speech communications or sleep. However, as background for creative activity, some high-level noise environments are considered satisfactory while low-sound-level environments containing information inimical to the listener are distracting and annoying.

Even in the residential context where routine family activity is all that is going on, certain sounds at almost any level have undesirable connotations. A new industrial plant that can just be heard, even though it is well below code requirements, would be acceptable in many communities with existing industry. It may not be accepted in a community if it were to move into an industrial zone that has not been occupied previously. The lack of acceptance, even of low-level noise in this case, obviously has social connotations.

RATING NOISE

Can we somehow rate these noise environments in terms of human acceptability? A look at some of the methods tried will indicate the success. It has been common at various times during the past 40 years to characterize noise environments by both single-number values, such as the widely used A-weighted sound level, and by the sound-pressure level in each octave band.

The A-weighted sound level was one of the earliest tools used to rate city noise. However, in the late 1940s the octave band levels were considered necessary to correctly characterize any sound. By 1970, those working in environmental noise were again almost exclusively attempting to use the A-weighted sound level for rating noise environments. Numerous schemes have been developed to measure the A-weighted sound level temporal statistics at one or more points in a community on a sampling statistics basis, and to use these statistics to define the noise climate in some way.

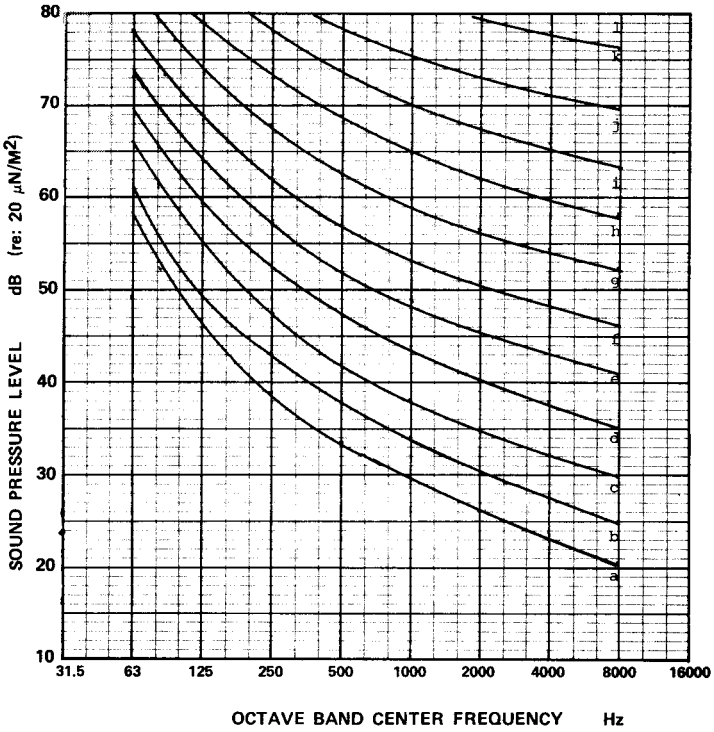
However, a close examination of the factors that influence human response will show why most proposed single-number rating schemes will fail in all but the simplest case. When rating methods are required to define the acceptability of an environment for residential use, be it one family houses, or apartments, or one or more large buildings, they often fail to consider a few susceptible individuals or people who carry on creative tasks at home, such as writers, composers, editors, and students.

A look at some of the more widely used current methods of rating noise environments should show the nature of the problem and the reason why and how each particular scheme fails—and they do fail.

Composite Noise Rating

This first appeared in 1954 in the Air Force's Handbook of Acoustic Noise

Figure 7.—Level rank curves for use in rating residential noise environments. The spectrum to be rated is drawn on the chart and the letter in the highest zone between the curves is assigned as the level rank. The level rank is adjusted according to table I to obtain the Composite Noise Rating or CNR.



Control and was later revised in a paper by Stevens, Rosenblith, and Bolt *(1955)*, and by Harris *(1957)*. The basic idea is to compare the spectrum and levels of a noise with a set of octave band contours labelled with lower case letters (fig. 7). The highest contour penetrated is called the *level rank* for the noise. The level rank is then changed one rank (the equivalent of a five-decibel step) for each of a series of adjustments related to season, time of day, ambient levels, duration, and character of the noise.

The resulting adjusted level rank is given a capital letter designation called the *Composite Noise Rating* (CNR). Use of the curves (fig. 7) allows an estimate based on experience to be made of the nature of community response by comparing the CNR to a table or curve of predicted response (fig. 8). The method is quite good, although it is claimed by Bishop *(1967)* to be less sensitive than it might be because of the five-decibel steps used. However, it has proved most effective where the correct data are supplied, particularly the duration of the intruding noises. Major drawbacks in using the CNR were the need for octave band spectra at several places in the community, along with duration information. This method was later adapted for an aviation noise response-prediction scheme jointly by the military and FAA *(1964)* for a land-use planning evaluation scheme for use around airports.

Community Noise Equivalent Level

This was developed by Wyle Laboratories *(1971)* for application to the airport noise monitoring problem. When

Table 1.—Correction numbers to be applied to noise level rank to yield Composite Noise Rating

Influencing factor	Correction number
1. Background noise:	
Type of neighborhood:	
Very quiet suburban	+1
Suburban	0
Residential urban	—1
Urban near industry	—2
Near heavy industry	—3
2. Temporal and seasonal factors:	
a. Daytime only	—1
Nighttime	0
b. Repetitiveness	
Source operates 20% of time in an 8-hour period	—1
Source operates 10% of time in an 8-hour period	—2
Source operates 2% of time in an 8-hour period	—3
c. Winter	—1
Summer	0
3. Character of the noise:	
a. Spectrum character:	
Continuous spectrum	0
Pure tone	+1
b. Peak factor:	
Smooth time character	0
Impulsive	+1
4. Previous exposure:	
None	0
Some	—1

Figure 8.—The predicted response of a community uniformly exposed to noise levels plotted on the level rank curves and adjusted according to table 1.

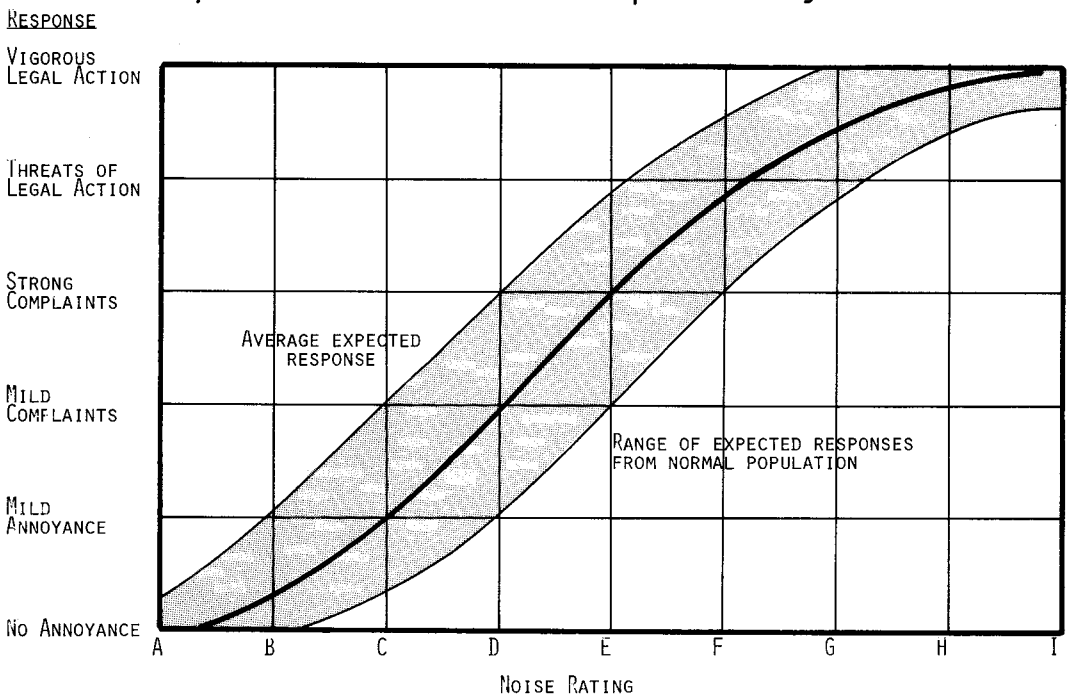
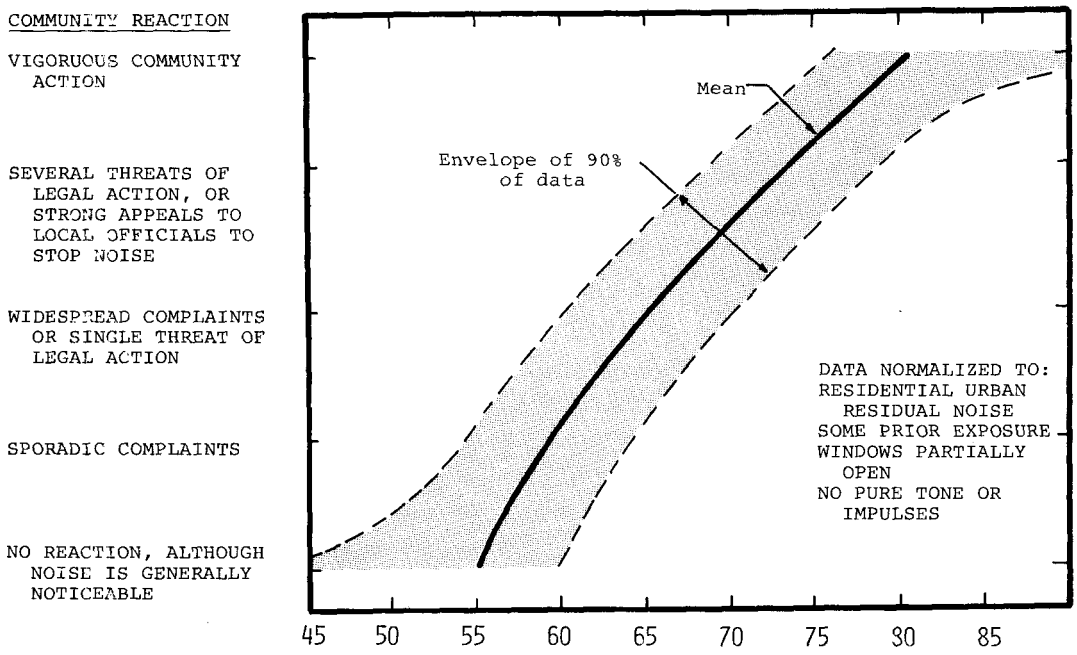


Figure 9.—The predicted response of a community may be obtained from the energy equivalent sound level in three periods—day, evening and night—using the equation shown below the figure. The figure shows the predicted response after adjustment according to table I.



$$CNEL = 10\ Log\ (\frac{1}{m+n+l})\ [\sum_{i=1}^{m} Antilog\ (DL_{10}/10)_i + 3\sum_{i=1}^{n} Antilog\ (EL_{10}/10)_i + 10\sum_{i=1}^{l} Antilog\ (NL_{10}/10)_i]$$

Where m, n, and l are the number of intrusive noise level values for day, evening, and nighttime sampling periods, respectively.

examining the problem of using a single number to describe the noise impact on a community from any kind of source, they found that the CNEL could be used as the evaluator of the physical exposure of members of the community. The CNEL is essentially the average of the hourly energy averaged A-weighted sound levels in three periods; day, evening, and night. This may be computed from the data by using the hourly L_{eq} (fig. 9).

The CNEL is then adjusted in the same way that the Composite Noise Rating was obtained and is normalized to the following conditions:

- Residential urban residual noise.
- Some prior exposure.
- Windows partially open.
- No pure tones or impulses.

These data may then be compared to table or chart to evaluate the probable community response (fig. 9).

ISO Draft Recommendation No. 1996

This suggests a method of measurement of noise, corrections to the measured level, and a means of using this corrected or rating sound level, for comparison with a community noise criterion *(ISO 1970)*. The community noise criterion considers various environmental acceptability factors.

The ISO draft recommends that noise should be measured by using a precision sound-level meter set at the A-weighting network and "fast" response. If the noise varies with time (as is the usual case for most nonindustrial environments), the rating is based on the energy equivalent level, L_{eq}. L_{eq} is defined as the "energy mean" of the noise, and for sampled data may be represented as a continuous, unvarying signal resulting in the same total energy each hour, or each day, as produced by the actual noise being measured.

The ISO recommendation suggests adding values to L_{eq} dependent upon the character of the noise and its duration, which results in a better estimate of the community's response to the noise. The resulting value is termed the "rating sound level", L_r.

The "rating sound level" might be considered the A-weighted sound level of a steady noise that does not contain any tonal or impulsive characteristics and produces the same community response. Hammering and riveting, it is suggested, are impulsive characteristics and require that +5 dB(A) be added to the rating sound level.

Two other methods for rating noise have been widely used. These are the Effective Perceived Noise Level in EPNdB, and the Noise Pollution Level.

Effective Perceived Noise Level

This is an extension of the aircraft noise rating method based on the noisiness curves developed by Kryter *(1959)* and applied by him to a broader noise-evaluation technique. It is basically a duration adjusted perceived noise level. It requires the use of the octave band spectra as input. The noise in question is evaluated on a band-by-band basis, using curves or a chart of noy — for noisiness — values for the level in each band. A summing scheme similar to that developed by S. S. Stevens *(1961)* in his loudness computation method, yields a summed noisiness value which may then be converted into the perceived noise level in PNdB. Adjustment for duration and pure tone content are made, and the result is the Effective Perceived Level.

Noise Pollution Level

This appears, at first glance, to have the right balance of the factors of level and duration to provide useful measure of noise impact. It was developed by D. W. Robinson *(1969)* who carried out a thorough analysis of a number of noise-rating methods and proposed that annoyance was related both to the total distribution of energy through the day — i.e., the exposure of the individual to the noise — and to a factor governed by the variation of level. He defined the Noise Pollution Level $NPL = L_{eq} + 2.56\sigma$ where σ is the standard deviation of the measured signal, assuming its distribution of levels as gaussian. This appears to be handy and rank orders numerous environments reasonably well.

However, the scale turns out to be somewhat compressed. Wyle Laboratories *(1971)* found that busy downtown areas had NPL values only slightly higher than suburban residential areas, judged by the public to be considerably less noisy. The strange result derives from the fact that downtown, the standard deviation is rather small — it is continuously noisy — although the L_{eq} is high, but out in the suburbs L_{eq} is low, but the standard deviation is high, as neighbors' cars and delivery vehicles come and go, and the sounds of children at play add to the range of σ. Finally, since community noise is not gaussian, the standard deviation has little or no meaning here.

Department of Housing and Urban Development Noise Criteria

The United States Department of Housing and Urban Development (HUD) has set acceptability criteria for new housing. The external noise standards are:

Category	*Standard*	*Environment*
Clearly acceptable	Does not exceed 45 dB(A) more than 30 minutes per 24 hours.	The noise exposure is such that both the indoor and outdoor environments are pleasant.
Discretionary: normally acceptable	Does not exceed 65 dB(A) more than 8 hours per 24 hours.	The noise exposure is great enough to be of some concern, but common building construction will make the indoor environment acceptable, even for sleeping quarters, and the outdoor environment will be reasonably pleasant for recreation and play.
Discretionary: normally unacceptable	Exceeds 65 dB(A) 8 hours per 24 hours; loud repetitive sounds on-site.	The noise exposure is significantly more severe so that unusual and costly building constructions are necessary to ensure some tranquility indoors, and barriers must be erected between the site and prominent noise sources to make the outdoor environment more tolerable.
Clearly unacceptable	Exceeds 80 dB(A) 60 minutes per 24 hours; Exceeds 75 dB(A) 8 hours per 24 hours.	The noise exposure at the site is so severe that the construction costs to make the indoor environment acceptable would be prohibitive and the outdoor environment would still be intolerable.

Day-Night Level

The L_{dn} is equivalent to the L_{eq24} with a 10 dB weighting applied to the equivalent level during the nighttime hours. The L_{dn} is defined as follows:

$$L_{dn} = 10 \log \frac{1}{24} [15(10^{Ld/10} + 9(10^{Ln/10})]$$

$L_d = L_{eq}$ for the daytime hours (0700 to 2200)

$L_n = L_{eq}$ for the nighttime hours (2200 to 0700)

The 10 decibel weighting was derived from several considerations: prior use of a nighttime weighting in other descriptors, and a normal difference in daytime and nighttime levels of 10 decibels. Descriptors such as CNR, NEF, NCNEL all use a weighting on the order of 10 decibels to adjust noise produced during the night to produce a more severe reaction on their response scales. The correction in these rating schemes, as well as L_{dn}, is designed to protect persons from possible sleep interference.

The assumption that equivalent sound levels for daytime and nighttime usually differ may be a valid one for urban and suburban communities, but in a rural suburban or rural community, this is rarely the case. Sound levels in rural areas are determined by distant events since local activity is low. Local activity causes the difference in daytime and nighttime levels, and an area lacking this activity will experience very little change from day to night with perhaps an increase at night due to insects. It is in this case that the usefullness of L_{dn} as a descriptor of impact is limited. A noise source may operate solely during the day, at levels comparable to the daytime ambient of, say, 45 dB(A); and

a similar level at night of 45 dB(A) may be produced by insects, resulting in an L_{dn} of 55. However, the EPA literature indicates that this level produces activity interference outdoors. Clearly the noise source is not causing the high L_{dn}, which indicates that care must be used whenever L_{dn} is used as a criterion.

DISCUSSION

Mathematical modelling techniques have proved useful in predicting the noise of a wide variety of projected facilities. Among the more widely used noise models are those for:

- Power-plant fans
- Cooling towers
- Air discharge and valve noise
- Highway traffic noise
- Railroad noise
- Aircraft

These models and some specially designed proprietary models for power plants and construction sites may be combined with analytical techniques to produce large-scale environmental models. Many models have been developed or modified for computer use. Others make use of nomographs, tables, and charts.

There are many situations where monitoring cannot identify which of multiple noise sources is the major contributor. Also, where changes to industrial plants are to be made or new transportation or industrial facilities are to be built, mathematical modelling of acoustical properties is a useful and reliable predictive technique.

We have shown that the range of outdoor noise levels is great, ranging from less than 30 to more than 90 dB(A). The methods that are close to actual field conditions for rating the acceptability of these various environments include factors that account for the social and geographic situation as well as the spectrum duration and the level of noise. No rating system is completely successful in rating environmental noise because it is difficult to characterize or quantify some of the factors that influence acceptability.

The final rating of environmental noise is always its acceptance or rejection by the community.

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Outside and Inside Noise Exposure in Urban and Suburban Areas

by DWIGHT E. BISHOP *and* MYLES A. SIMPSON, *Bolt Beranek and Newman Inc., respectively at Canoga Park, Calif., and Arlington, Va.*

ABSTRACT.—In urban and suburban areas of the United States (away from major airports), the outdoor noise environment usually depends strongly on local vehicular traffic. By relating traffic flow to population density, a model of outdoor noise exposure has been developed for estimating the cumulative 24-hour noise exposure based upon the population density of the area. This noise model has been used to provide first-order estimates of noise exposure in urban areas of this country. The model also can be used to estimate the variation in noise levels in communities and to plan community noise surveys. Field measurements at 100 locations throughout the country have shown good agreement with this model.

THE OUTDOOR NOISE environment in urban and suburban areas in this country is due to many different noise sources of varying frequency content and temporal characteristics. Actual noise levels and noise exposures vary over a considerable dynamic range. However, because of the prevalence of similar major sources of noise, one can expect many similarities in noise exposure and in daily patterns of noise exposure throughout the country. These similarities suggest that there should be good likelihood of developing useful models for predicting the noise environment for different neighborhoods throughout the country.

Because of the well-identified and relatively well-studied impact of jet-aircraft noise and high density freeway traffic noise, rather detailed analytic models have been developed for predicting aircraft and highway noise. These models are quite accurate for locations relatively close to the noise sources. Although aircraft operations and freeway traffic produce some of the noisiest outdoor environments found in this country, only a small proportion of the total population is exposed to these rather intense noise sources. The majority of the population is affected by noise from other sources. A means for defining the noise exposure for this large segment of the population that does not depend upon detailed knowledge of source levels, operating conditions, or identification of specific noise sources is particularly useful for community and land-use planning.

This paper discusses a simple model for estimating the noise exposure in urban and suburban areas not located near airports or major freeways. The paper also discusses measurements made to confirm and verify this model and also provide additional information about typical urban outdoor and indoor noise environments.

An emphasis on the outdoor noise environment sometimes obscures the fact that most of us spend much of our lives indoors, and that actually, our noise exposure is not necessarily predicted well from knowledge of the outdoor noise levels alone. Thus, to provide some perspective, this paper also presents a brief comparison of simultaneous indoor and outdoor measurements made in residential areas.

Before describing the noise model and measurements, we should first define the

kind of noise measure that we will use. All measurements will be reported in terms of the A-weighted noise level in decibels. This level incorporates a frequency weighting of the noise signal similar to that of the human ear; it thus provides a reasonably good assessment of the noise in terms of people's subjective response to noise.

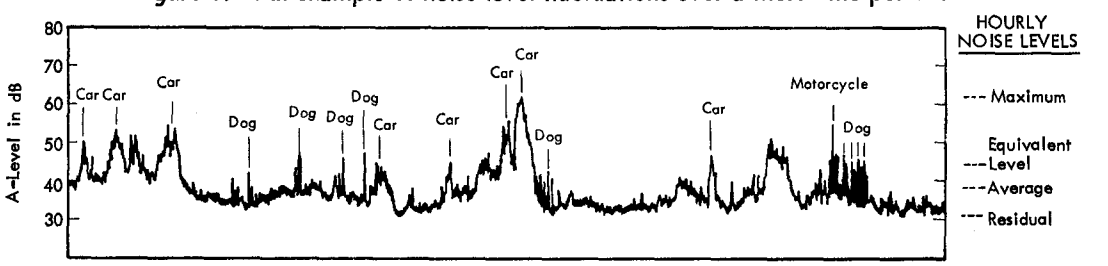
Because of the time-varying nature of the actual noise environment, the temporal aspects of noise must also be considered in selecting a useful scale for measuring the noise environment. Given modern acoustic instrumentation and digital computers, it is now easily possible to develop detailed and exhaustive statistical descriptions of the noise measured over any desired time period, ranging from a few minutes to a few years. However, for many planning purposes, such detail is not needed nor desired. Thus, in this paper the noise environment will be described in terms of the A-weighted *equivalent level* measured over hourly periods or measured during the 24-hour day.

For those not familar with the concept, the *equivalent level* is obtained by "energy" averaging the noise levels occurring over a stated period of time, an hour or day, for example. The equivalent level is equal to the level of a *continuous* noise source that would produce the same energy as contained in the actual fluctuating noise levels occurring over the same time period. Figure 1 shows a graphic level recording of the actual noise levels measured over a short (14-minute) time. The equivalent level noted on the figure may be compared to the maximum level observed during the period and the "arithmetic" average level existing over the period. The equivalent level is much more influenced by the presence of short duration noise intrusions than is the "mean" or "median" noise level.

To describe the noise environment over a 24-hour day, the day-night average level (L_{dn}) measure will be used. The day-night average level extends the equivalent level concept to the entire 24-hour period, but includes a weighting of 10 dB applied to the noise levels measured at night (taken as the period from 10 P.M. to 7 A.M.). This weighting is applied to reflect the greater sensitivity to noise in residential areas during the night.

Other measures of the noise environment are in more or less common use and are described in the literature. For most community noise environments, the correlation of one noise measure with another will generally be quite high. Thus, with the exception of neighborhoods exposed to discrete high-level noise intrusions (such as neighborhoods near jet airports), general conclusions based on day-night levels or hourly equivalent levels will hold for most other noise measures in common use.

Figure 1.—An example of noise-level fluctuations over a short time period.



HISTORY OF NEIGHBORHOOD NOISE, A 14 MINUTE SEGMENT FROM A ONE HOUR RECORD

BASIC MODEL ASSUMPTIONS

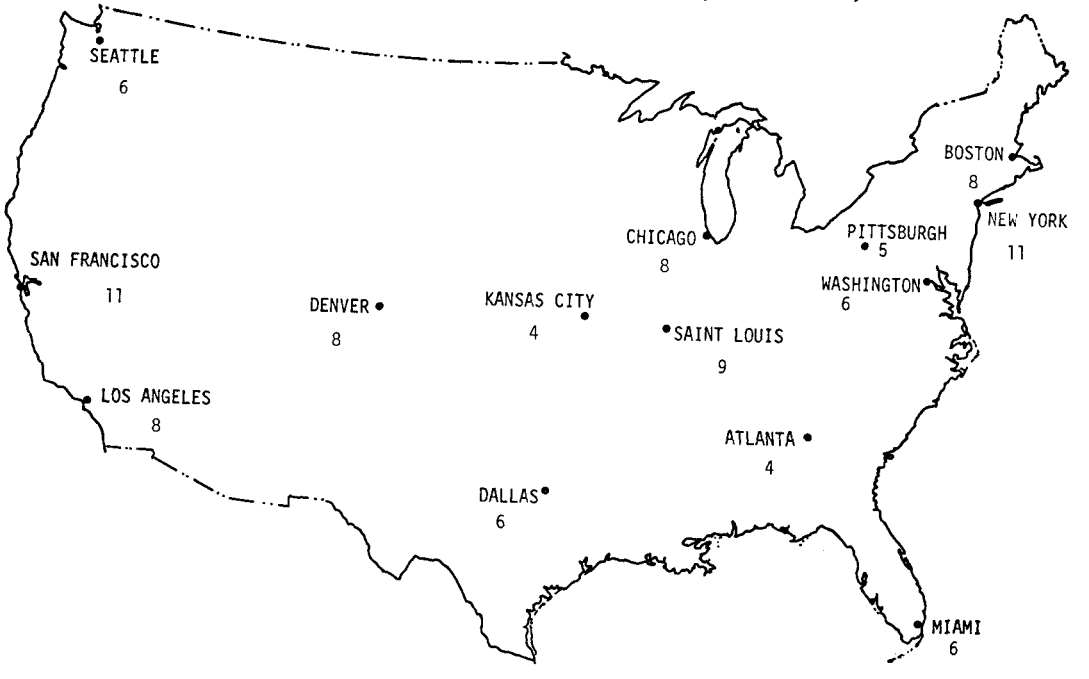
The impetus for developing this noise model arose from the need of the United States Environmental Protection Agency to estimate the outdoor noise exposure for the entire urban and suburban area of the United States. Evidence from community noise surveys pointed out clearly that surface transportation was the most important single contributor to the noise environment. Over a wide range of population densities and of total populations, the number of automobiles per person is almost constant, as is the ratio of trucks in service to automobiles in service. Thus the use of vehicles is directly proportional to population density. If nonfreeway traffic is considered, the average speed of motor vehicles in urban areas is essentially constant. Application of existing traffic noise models then suggests that as a first-order estimate, the community noise level should be proportional to 10 times the logarithm of the population density of the community.

This hypothesis was first tested against 30 examples of existing noise data. It was found that the day-night sound level could be correlated with 10 times the logarithm of the density per square mile with an intercept of 32 dB for a population density of 10 people per square mile.

NOISE SURVEY MEASUREMENTS AND ANALYSIS

To obtain more substantiation of this model, a program was set up to measure noise at 100 locations throughout the country. Selection of measurement sites was governed by consideration of the availability of census data, variations in population density, geographic spread of communities, and the need to select sites away from major highways and airports. Figure 2 shows the cities included in the noise survey; the number of sites

Figure 2.—Cities included in the Community Noise Survey.



measured in each city is also shown in the figure.

The central city average density varied among the cities selected from a low of approximately 2,100 in Kansas City to a high of 26,300 in New York City. The field measurements were made in community areas having population densities ranging from slightly over 1,000 per square mile to approximately 90,000 people per square mile.

Measurement sites were restricted to areas not closer than approximately 1,000 feet from major highways and where the estimated noise exposure to aircraft noise was less than an L_{dn} value of 70 dB. At each site, the microphone was located 1.8 meters from the building facade. The microphone was typically located 1.5 meters above the ground for single-story residences. For multi-story residences, the microphone was placed at an elevation comparable to occupant height.

Figure 3-4.—Samples of noise data obtained from a 24-hour site measurement.

SITE # 1303

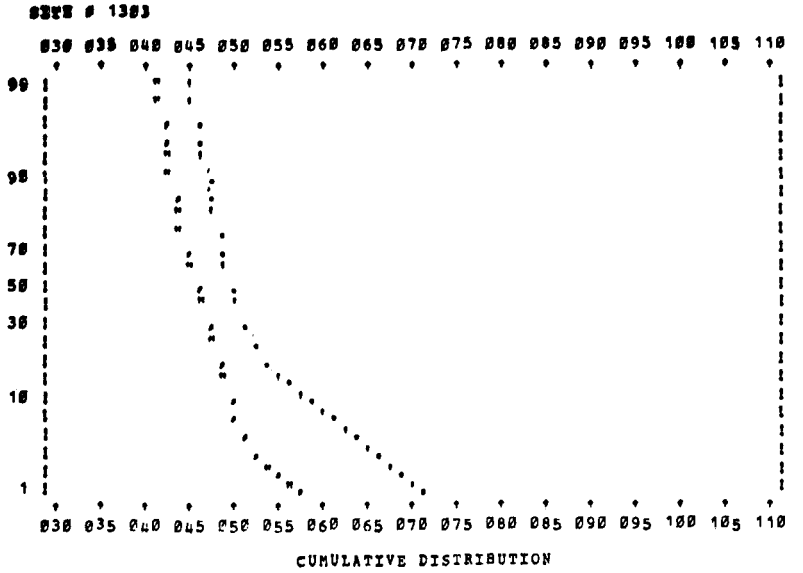
HR	MAX	MIN	NPL	SIG	LEQ	TNI	L1	L3	L5	L10	L20
1	68.8	42.5	55.0	2.4	48.9	29.4	58.0	54.8	52.2	48.9	48.3
2	68.8	42.5	50.5	1.6	46.4	26.3	51.2	48.4	47.5	47.2	46.4
3	71.3	41.3	54.8	2.8	47.7	28.5	60.6	51.4	48.4	46.8	45.9
4	62.5	40.0	50.0	1.8	45.3	26.9	52.8	48.2	47.0	46.1	45.6
5	76.3	43.0	54.0	2.7	47.0	25.9	58.7	49.6	46.6	45.3	44.6
6	68.8	40.0	54.0	2.8	46.8	34.3	56.9	51.1	49.6	47.7	46.0
7	76.3	42.5	62.3	3.7	52.9	37.0	65.6	58.6	53.5	50.6	48.7
8	70.0	42.5	56.7	2.7	49.9	37.1	59.7	55.2	53.3	51.2	49.7
9	71.3	42.5	57.8	2.8	50.6	36.1	60.8	56.2	54.0	51.3	49.8
10	81.3	45.0	67.5	4.2	56.9	40.8	70.0	64.9	59.7	53.7	51.3
11	70.0	43.8	56.7	2.4	50.7	33.0	60.9	53.6	52.0	50.9	49.9
12	83.8	43.8	63.5	3.5	54.6	46.3	63.8	58.8	56.9	54.9	53.4
13	82.5	43.8	65.5	3.9	55.6	40.1	65.4	59.4	55.9	51.7	49.9
14	77.5	45.0	63.3	3.7	53.9	43.2	66.1	62.0	58.7	54.1	50.7
15	76.3	43.8	57.8	2.6	51.0	36.1	58.6	52.4	51.4	50.8	49.9
16	75.0	43.8	60.0	2.9	52.5	34.2	64.0	58.7	55.3	51.9	50.4
17	81.3	43.8	60.9	3.2	52.7	39.6	63.2	57.0	54.3	52.2	50.9
18	86.3	47.5	70.1	4.4	58.9	51.6	70.8	65.5	62.3	57.4	53.6
19	98.8	45.0	84.5	7.0	66.6	84.9	77.6	72.4	69.6	65.3	60.3
20	92.5	46.3	79.0	5.9	63.9	72.3	75.9	69.4	66.3	62.5	58.6
21	93.8	46.3	86.0	7.2	67.6	92.2	79.5	75.4	73.0	69.0	64.6
22	90.0	46.3	66.6	3.7	57.2	43.5	68.3	62.2	59.2	55.2	52.4
23	65.0	46.3	53.7	1.4	50.1	29.1	55.9	53.8	52.6	51.1	50.1
24	67.5	43.8	52.8	1.6	48.7	28.9	55.6	51.5	50.4	49.7	48.9

HR	L30	L40	L50	L60	L70	L80	L90	L95	L97	L99
1	47.9	47.5	47.2	46.9	46.6	46.3	45.3	44.6	44.3	43.9
2	46.1	45.8	45.5	45.3	45.0	44.5	44.1	43.9	43.8	43.0
3	45.4	45.0	44.5	44.1	43.7	43.3	42.8	42.6	42.5	41.8
4	45.0	44.8	44.5	44.2	44.0	43.6	42.5	41.9	41.6	41.4
5	44.1	43.6	43.3	43.0	42.7	42.3	41.7	41.4	41.3	40.7
6	45.0	44.5	43.9	43.5	43.1	42.8	42.2	41.7	41.5	41.3
7	48.0	47.4	47.0	46.6	46.2	45.7	45.2	44.6	44.2	43.9
8	48.7	48.3	47.8	47.4	47.0	46.6	45.9	45.4	45.1	44.4
9	49.1	48.6	48.2	47.8	47.4	46.9	46.3	45.6	45.3	44.6
10	50.7	50.1	49.7	49.4	49.0	48.7	48.0	47.7	47.6	46.8
11	49.5	49.1	48.7	48.3	48.0	47.6	46.9	46.5	46.3	45.5
12	52.3	51.0	49.9	49.2	48.6	48.2	47.7	47.5	46.9	46.3
13	49.1	48.5	48.0	47.6	46.9	46.2	45.6	45.2	45.1	44.7
14	49.8	49.5	49.1	48.8	48.5	48.1	47.8	47.6	47.6	47.2
15	49.2	48.5	47.6	47.1	46.7	46.3	45.7	45.3	45.2	45.0
16	49.8	49.6	49.3	49.0	48.8	48.3	47.8	47.5	46.8	45.6
17	50.0	49.4	48.8	48.1	47.4	46.9	46.4	45.8	45.5	45.1
18	52.4	51.8	51.2	50.8	50.4	50.0	49.4	49.0	48.9	48.8
19	57.1	54.6	52.7	51.3	50.3	49.5	48.8	48.0	47.6	46.8
20	56.1	54.3	52.9	51.7	50.8	50.0	49.2	48.8	48.4	47.8
21	61.1	58.6	56.5	54.9	53.5	52.3	51.3	50.3	49.8	48.9
22	51.8	51.2	50.8	50.4	50.0	49.5	49.1	48.8	48.7	47.9
23	49.8	49.6	49.4	49.2	49.1	48.9	48.4	47.9	47.8	47.6
24	48.5	48.3	48.0	47.8	47.5	47.0	46.6	46.4	46.3	45.7

Sample Output Listing

A-weighted noise levels were monitored continuously for a full 24-hour period at each site, using portable unmanned monitoring systems we had developed. These systems sampled the noise environment at a rate of 8 times per second. For each sample, the noise signal was A-weighted, converted to a decibel format, and distributed into 1 of 64 bins, each 1.25 dB wide spanning a sound level range from 30 to 110 dB. Once each hour, the contents of the 64 bins as well as the time of day were recorded on a digital tape.

The data tapes were later processed by computer to yield various noise-level statistics and measures for each hour as well as for daytime and nighttime periods. Figures 3 and 4 show a sample output listing for one of the sites. Various statistics describing the cumulative distribution of noise levels occuring for each hour and for the daytime and nighttime periods are tabulated. Also tabulated are the maximum and minimum noise levels, as well as other noise measures, including the equivalent level and the day-night level. Cumulative distribution curves of the daytime and nighttime noise levels are also plotted.



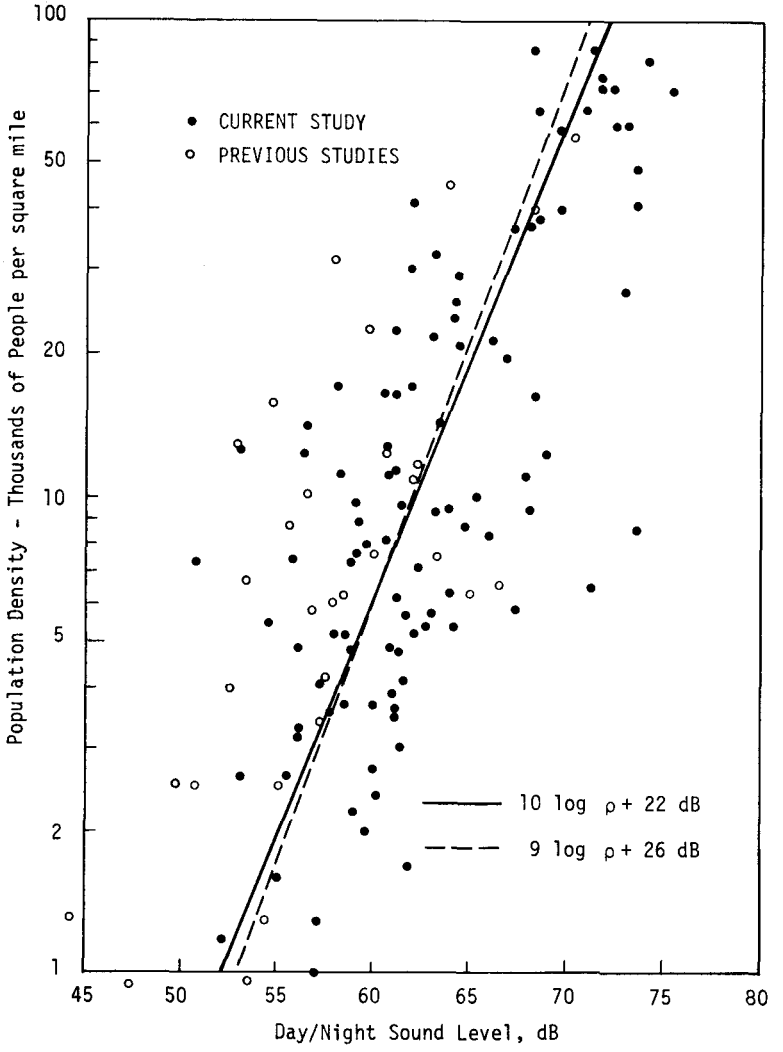
	DAY '.'.	NIGHT ","	WEIGHTING	WEIGHTED L_{eq}
MAX	98.8	76.3	0.	58.7
MIN	42.5	40.0	8.	59.5
MDL	74.0	56.7	10.	60.0
SIG	5.2	3.1	12.	60.7
LEQ	60.6	48.8		
TNI	60.4	39.6		
L1	71.9	57.6		
L3	66.0	52.5		
L5	62.7	50.8		
L10	57.8	49.6		
L20	53.3	48.5		
L30	51.4	47.6		
L40	50.5	46.7		
L50	49.7	46.0		
L60	49.2	45.2		
L70	48.6	44.5		
L80	47.9	43.9		
L90	46.9	42.9		
L95	46.2	42.4		
L97	45.7	41.9		
L99	45.2	41.4		

Sample Output Listing

The day-night levels observed over the 100 sites range from approximately 50 to 75 dB. Figure 5 shows the measured day-night levels plotted vs. the logarithm of the population density. The computed least squares regression line yields an equation showing that L_{dn} is equal to 9 times the logarithm of the population density plus 26 dB. The regression line has a correlation coefficient of 0.72 and a standard error of the estimate of about 4 dB.

If we assume that the noise level varies with 10 times the logarithm of the population density, the model indicates an intercept of 32 for a population density of 10. At the 5-percent level of significance, this regression line with a slope of 10 is statistically insignificant from the least square regression line. Thus, the equation showing L_{dn} equal to 10 log population density plus 22 provides a useful first-order estimate of outdoor levels in urban residential areas in this country.

Figure 5.—Correlation of day-night levels with population density.



Day/Night Sound Level as a Function of Population Density

MODEL APPLICATIONS

If one assumes that at each level of population density, the L_{dn} values are normally distributed about the average level (given by the model equation) with a standard deviation of the same order as the standard error of the regression line (4 dB), one can then estimate the noise exposure for the country, given the population density distribution of the urban population in the United States. This was done, using population-density information for census tracts, obtained from the 1970 census. Some results are given in table I (more detailed results are given in Galloway 1973).

Table I.—Estimated community noise exposure in the United States*

L_{dn} in dB	Number of people exposed to specified L_{dn} or greater
	Millions
55	93.4
60	59.0
65	24.3
70	6.9
75	1.3
80	.1

*Excluding freeway and airport noise.

This analysis indicates that more than 90 million people live in areas with day-night levels in excess of 55 dB, and 1.3 million people live in areas with day-night levels in excess of 75 dB.

The population-density model also provides a basis for estimating the variation of noise levels throughout a community and as a basis for planning detailed community noise surveys. In this approach, noise levels derived from estimates of the population density can be viewed as setting a "plateau" noise level for community areas that are not located near strong localized noise sources. Then, to this plateau, one can add the "ridges" and "mountains" contributed by the noise of strong sources (major highways, railroads, and industrial noise sources as well as aircraft).

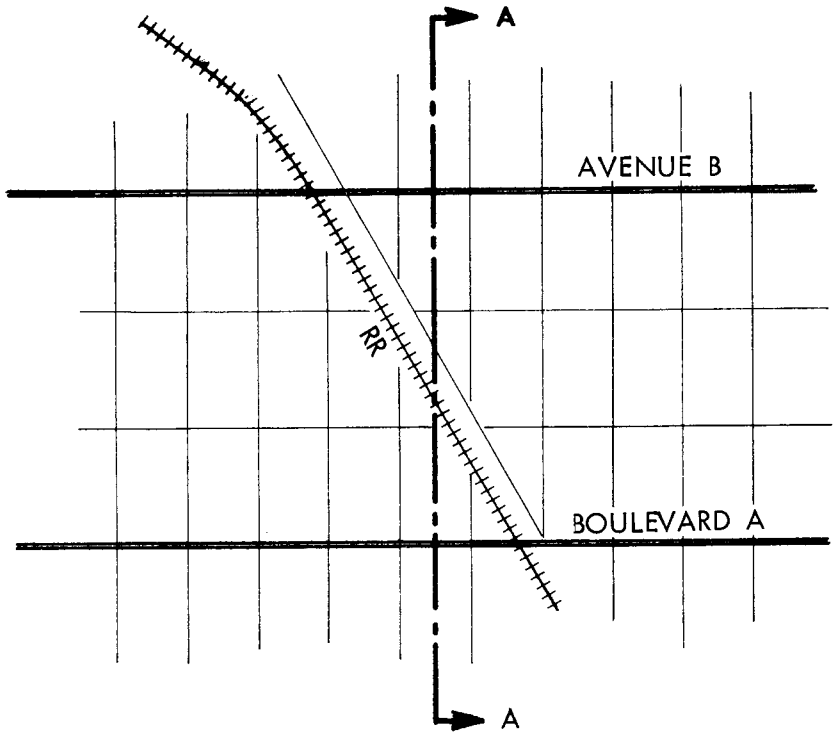
Figure 6 shows this application to a hypothetical community area. The community area of interest is bordered by two major roadways and is intersected by a railroad. The lower portion of the figure shows an estimate of the noise levels throughout Section AA. The plateau noise level given by the population density is shown as is the contribution by the surface traffic sources. This profile may be used to provide first-order estimates of the differing noise exposure through the cross-section. It also provides a basis for initially locating noise-measurement positions for a detailed field-noise survey.

DAILY NOISE-LEVEL TIME PATTERNS

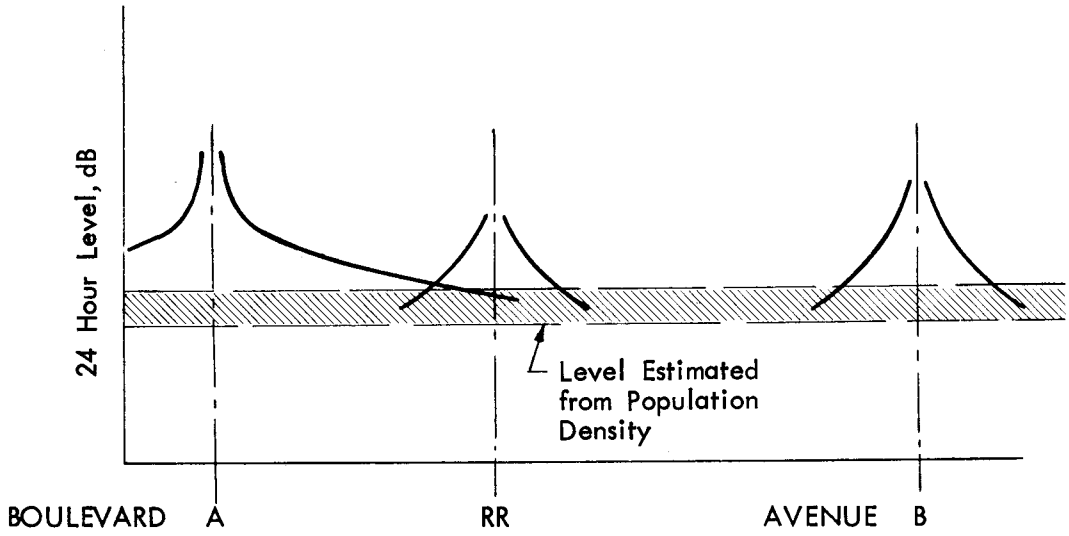
The information collected at the 100 sites throughout the country provided much information in addition to the 24-hour L_{dn} data. The data, for example, provide some insight into the typical variations in noise levels during different times of the day. Figure 7 shows the composite daily noise pattern where the average equivalent level for each hour of the day (across the 100 sites) is plotted as a function of time of day. At each site, the hourly values have been referenced to the day-night level for that site. Thus, the figure shows the difference between the 24-hour day-night average level and the equivalent level for each hour of the day.

Since the difference between the equivalent level at any one hour and the day-night level generally differs from site to site, one can obtain a measure of a variability in relative noise levels with time of day by computing the standard deviation for those differences for each hour of the day. This information may be useful, for example, in determining the best time of day in which to take measurements, i.e. in determining which hourly measures would provide the most reliable estimates of the

Figure 6.—Using the population density model to predict noise-level variations in a community area.

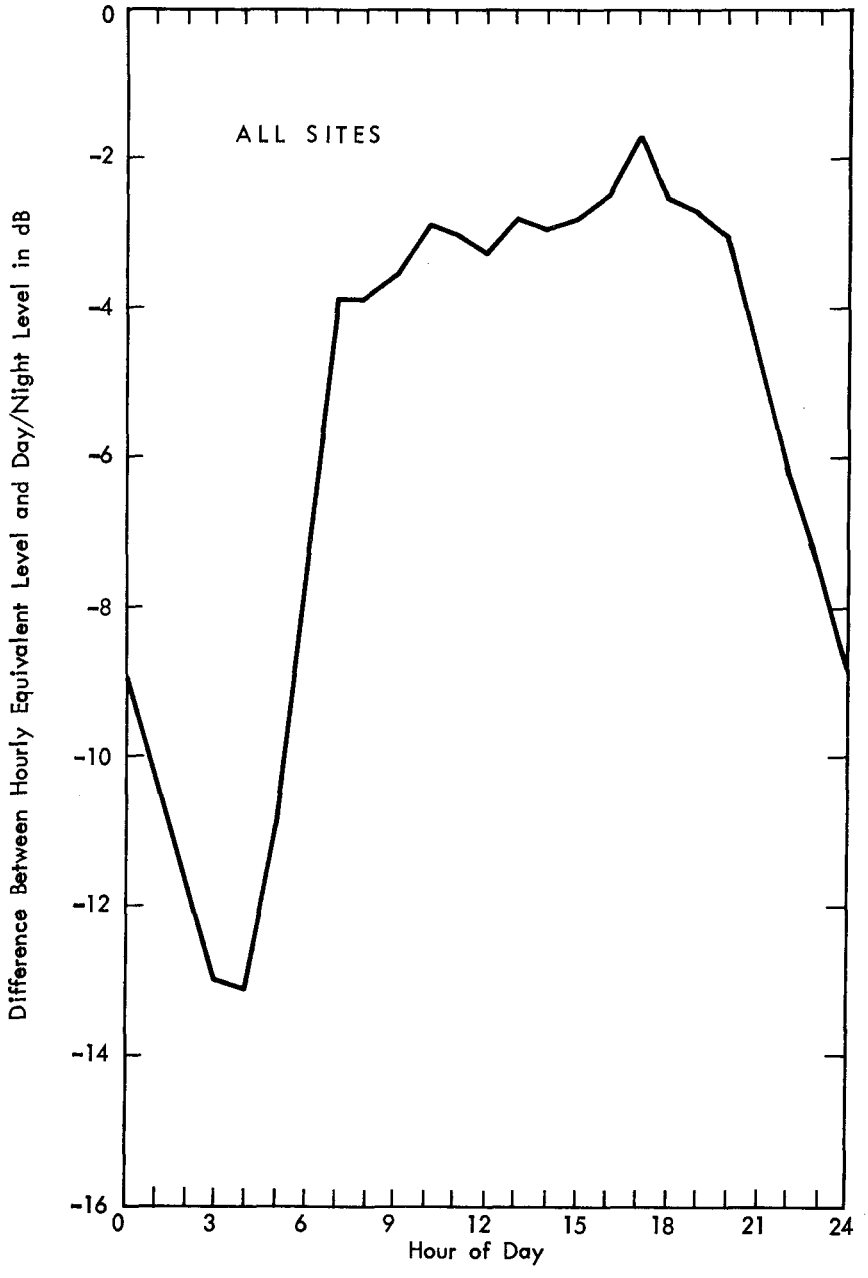


A. MAP OF NOISE SURVEY AREA



B. NOISE LEVEL PROFILE THROUGH SECTION A-A

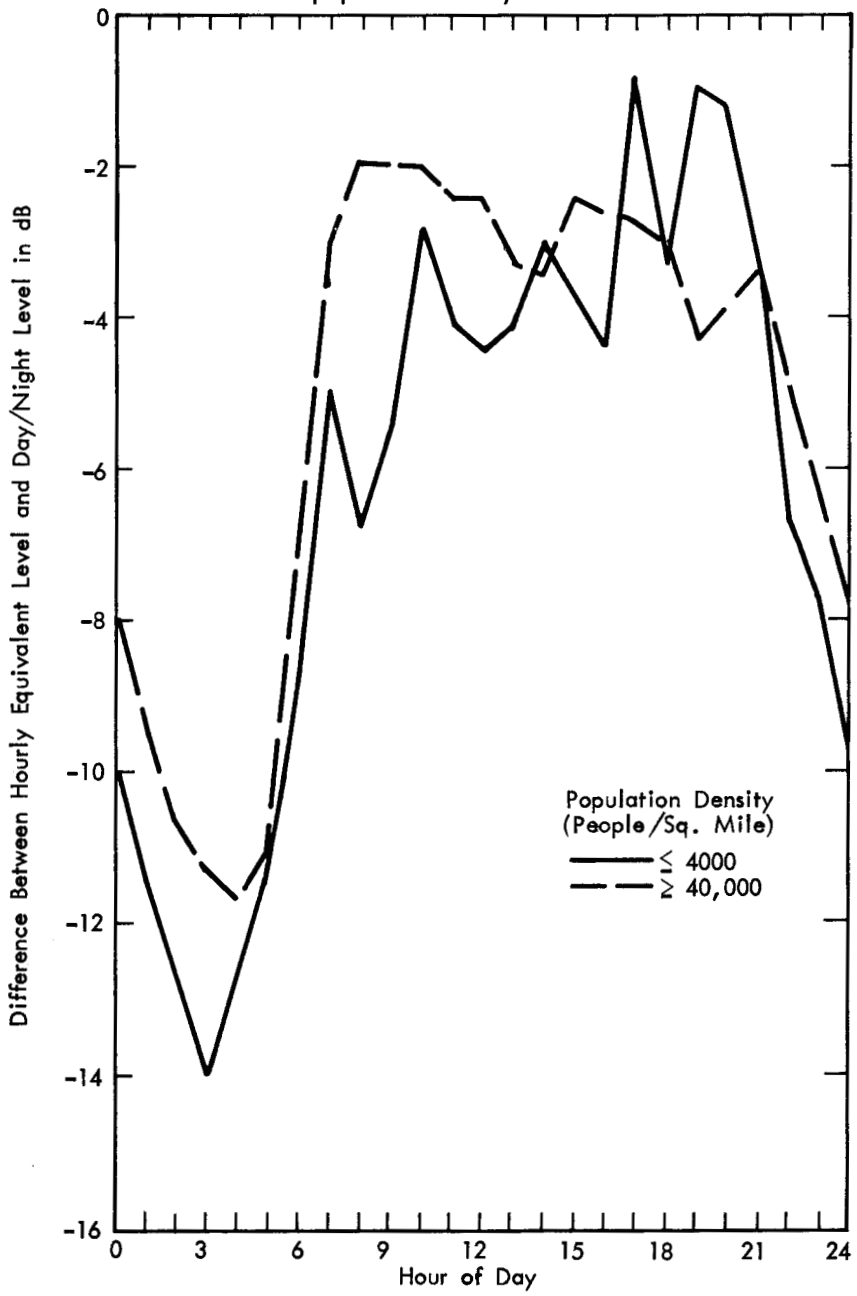
Figure 7.—Average hourly time patterns of noise levels (100-site survey).



24-hour noise exposure. For the data shown in figure 7, the standard deviations of the hourly averages range from about 4 dB in the early morning hours, generally decreasing through the day to about 2.5 dB in the late evening.

One can examine these daily patterns for sites having different population densities to check if there are differences in patterns for areas having greatly different densities. Some can be anticipated, since the daily traffic flow patterns may differ between high and low density urban areas. As an example, figure 8 shows the variation in hourly noise levels for sites with: (a) popula-

Figure 8.—Hourly time patterns of noise levels for sites of widely different population density.



tion densities of 4,000 persons per square mile or less; and (b) population densities of 40,000 people per square mile or greater.

Several interesting trends can be noted in the comparison. For the lower density sites the range in noise levels from minimum nighttime levels to maximum daytime levels is greater—approximately 13 dB compared to 10 dB for the higher density areas. This confirms earlier measurements showing

smaller variations in levels for areas exposed to heavier volumes of daily traffic *(Bishop and Simpson 1973)*.

Another interesting finding is that, in the high-density areas, the noise levels show less variation during the day, with levels reaching a maximum early in the morning and decreasing slightly during the day. In the low-density neighborhoods, more typical of suburban residential areas, the pattern shows a general rise in the noise levels during the day, with a maximum occurring between the hours of 5 and 9 P.M.

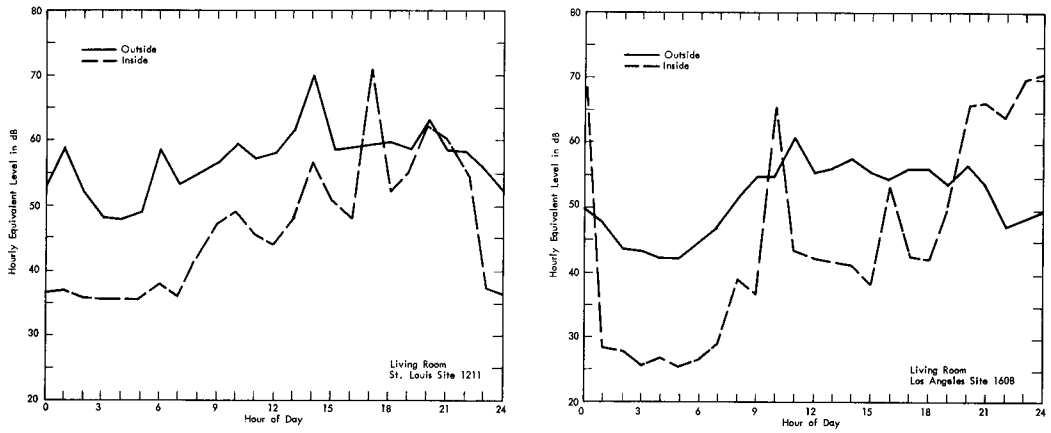
COMPARISON OF INSIDE AND OUTSIDE NOISE LEVELS

Thus far we have concentrated on descriptions of the outdoor noise environment; but most of our time is spent inside buildings, and the noise environment inside a building can bear little relationship to the environment measured outdoors. Thus, it is important to have some knowledge of the correlation of inside and outside noise environments. Sometimes too much importance may be placed on the control of exterior noise if one neglects the noise that is generated by people activity inside a building and the noise resulting from use of appliances, tools, radios, and televisions. Of course, we must remember that much of the noise generated inside a building may be wanted noise and even essential. In contrast, most noise intrusions from the outside are generally undesired.

Typically, in moderately quiet neighborhoods, we would expect the indoor noise environment to be controlled primarily by internally generated noise sources. It is only in relatively noisy outdoor environments that the noise leaking in from the outside contributes measurably to the indoor noise environment. There are extremely wide variations in the noise patterns found in different rooms of a building, depending, obviously, on the degree and kinds of activities.

Figure 9 shows the inside and outside measurements made in two different living rooms. The patterns here show some fairly predictable patterns. In both living rooms, the noise levels during late night hours (from midnight until about 6 or 7 in the morning) fall well below the outdoor noise levels. It is during this night period that exterior noise events most noticeably influence the indoor noise patterns. During the day, both indoor and outdoor noise levels increase, with a marked increase of indoor noise

Figure 9.—Comparison of indoor and outdoor noise levels at two residential sites.



to a maximum during the evening hours when the living room is either occupied or activities are occurring in adjacent areas of the house.

SUMMARY

Field noise measurements consisting of sets of 24-hour measurements made at 100 residential sites scattered across the country confirm a simple model for estimating the community noise environment based on knowledge of the site population density. This model has been used to provide a first-order estimate of the noise exposure in urban areas of this country. The model also can be used in estimating the variation in noise levels in community areas and in planning detailed community noise surveys. Data obtained from the 100-site field study have also yielded considerable information on the time pattern of noise levels occurring during the 24-hour day. Simultaneous inside and outside measurements in residences confirm the general lack of correlation between inside and outside noise levels, which result from the noise generated by people's indoor activities.

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Study of Traffic Noise Levels at Various Heights of a 39-Story Building

by NORMAN L. MEYERSON, *vice president, Ostergaard Associates, Caldwell, N. J.*

ABSTRACT.—Comparative measurements of exterior noise levels made at floors 3, 14, 26, and 37 of a high-rise apartment tower, when presented as a statistical distribution of percent exceedance vs. decibels, show the nature of the influence of local traffic at the low floors compared to the influence of an area source at the high floors. The open window penalty to interior noise levels was measured as well as the side street noise propagation along the building from avenue vehicular traffic sources alone.

THE IMPOSITION OF NOISE-EXPOSURE limits on new urban multi-unit living quarters as a prerequisite to acceptability for government financial assistance has encouraged attention to this matter early in the design stage. The U. S. Department of Housing and Urban Development (HUD) criteria tend to discourage the construction of new dwelling units, including the rehabilitation of older dwellings, by withholding HUD financial assistance if there are, or are projected to be, unacceptable interior or exterior noise exposures.

HUD Circular 1390.2 specifies exposure standards in terms of categories termed broadly as; "Unacceptable", "Discretionary", and "Acceptable" as measured at appropriate locations along, and heights above, site boundaries. In New York City, local interpretation has extended the locations to the facades of the projected or existing buildings because most buildings do in fact start at the site line or very close to it. The external noise standards are fundamental to realizing an acceptable level of noise in the occupied or dwelling areas of the building, with specific emphasis on sleeping quarters. Performance standards limiting interior noise exposures as stipulated in Circular 1390.2 are predicated on "open windows unless other provision is made for adequate ventilation".

The sponsors of high-density housing, such as high-rise apartment buildings, are sensitive to the need to introduce measures to combat noise intrusion. This is particularly so because significant economies are realized when it can be established that, for a particular design, a majority of the living units meet the noise requirements without resorting to costly acoustic measures involving shifts in window exposures, insertion of high transmission loss window assemblies, installation of room or centralized comfort conditioning, etc. Just such a consideration precipitated the request for an evaluation of traffic noise exposure at various elevations on the avenue side of a 39-floor high-rise tower (figs. 1 and 2) and along the avenue side of a flanking L-section wing having 7 floors (figs. 3 and 4). The building is located in midtown Manhattan, fronting on a moderately used north-south avenue and between lightly used cross streets.

Before construction of the building, measurements at the site revealed that the external noise exposure at the avenue side of the tower and at the elevation of the projected lowest residential floor was "Discretionary—Normally Unacceptable" (fig. 5) since the distribution curve passed to the right of the stipulated transition point (X in fig. 5) between being normally unacceptable and normally acceptable. This was



Figure 1.—The 39-floor high-rise tower studied in New York is provided with room air-conditioner openings in the avenue exposure side of the building.



Figure 2.—The entrance and lower levels of the tower structure.

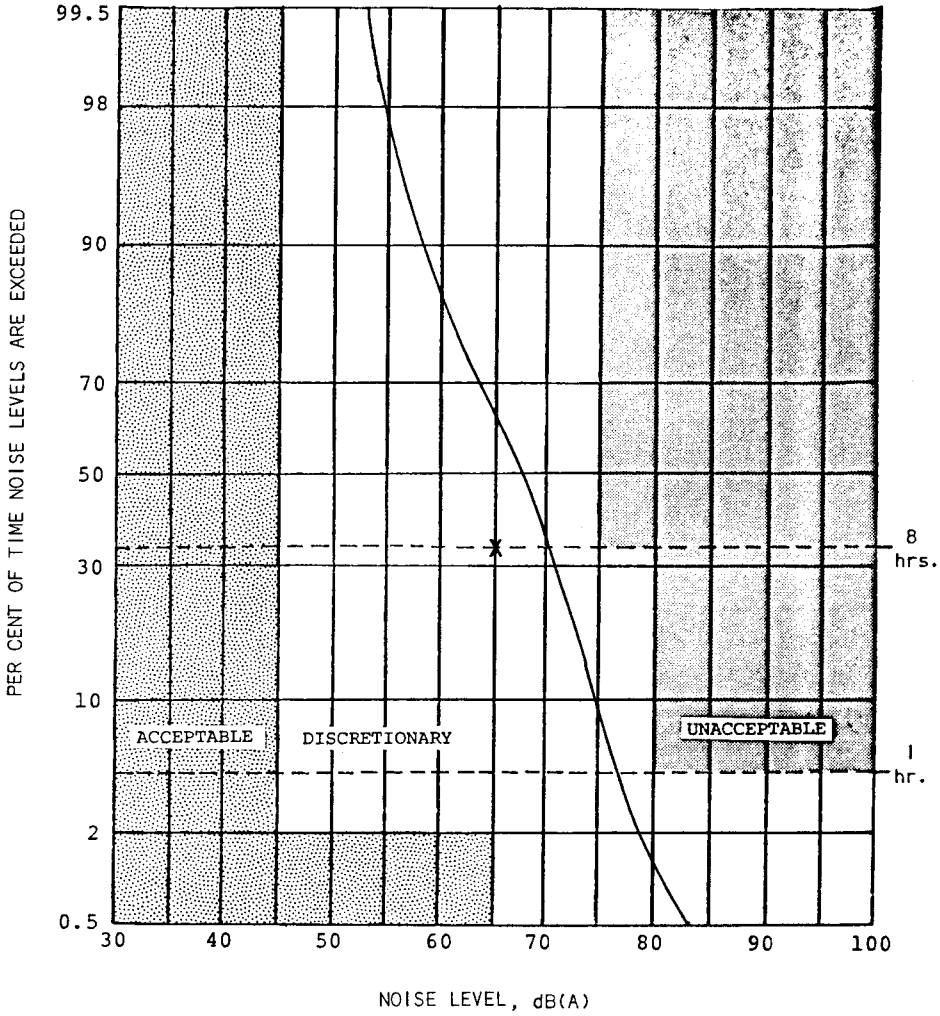
Figure 3.—The avenue side of the seven-floor L-section wing adjacent to the tower structure.



Figure 4.—A side-street view of the seven-floor L-section wing.



Figure 5.—Statistical exceedance distribution of recorded noise levels over a period of 24 hours at the building site before construction. Traffic in the area at the time of the tests was determined to be mid-week normal with no local street closures or disruptions. HUD Circular 1390.2 exterior criteria has been superimposed. Measurements were taken at the lowest projected bedroom elevation and at the building line.



based on a 24-hour midweek measurement showing the exterior noise level to exceed 65 dBA for more than 8 hours. Subsequent to this reporting, the building was erected and a repeat test was requested. Because of several important deterrents, the 24-hour test could not be repeated with any degree of reliability. Closing of a hazardous nearby highway caused a redistribution of avenue traffic, and construction activity on nearby streets prompted this decision.

Accepting the premise that the normally unacceptable but discretionary exposure prevailed, and that measures must be taken to assure maintaining interior levels within criteria, a study was sponsored to determine the height at which the external noise standards would meet the discretionary but nor-

mally acceptable criteria. All apartments below this level would then be considered for mitigating measures by architectural and mechanical modification.

For exterior measurements at all selected locations, windscreen-fitted microphones attached to booms were extended out from the building facade to a distance of 1 meter and oriented for random incidence. Simultaneous A-weight recordings were made on tape recorders at several levels of the building tower; floors 3, 14, 26, and 37 were selected for approximate equidistance. Since the readings were directly comparable, the level of traffic flow was essentially immaterial; however, to obtain a range of noise levels, testing was started early enough to include rush-hour traffic.

Graphic record comparisons were possible for recordings taken on the 3rd and 14th floors, but the smoother noise variations observed at the 26th and 37th floors made statistical analysis mandatory. Accordingly, analysis samplings of the simultaneously recorded data were

Figure 6.—Statistical exceedance distribution of simultaneously recorded noise levels over a 3-hour sampling period for four tower elevations.

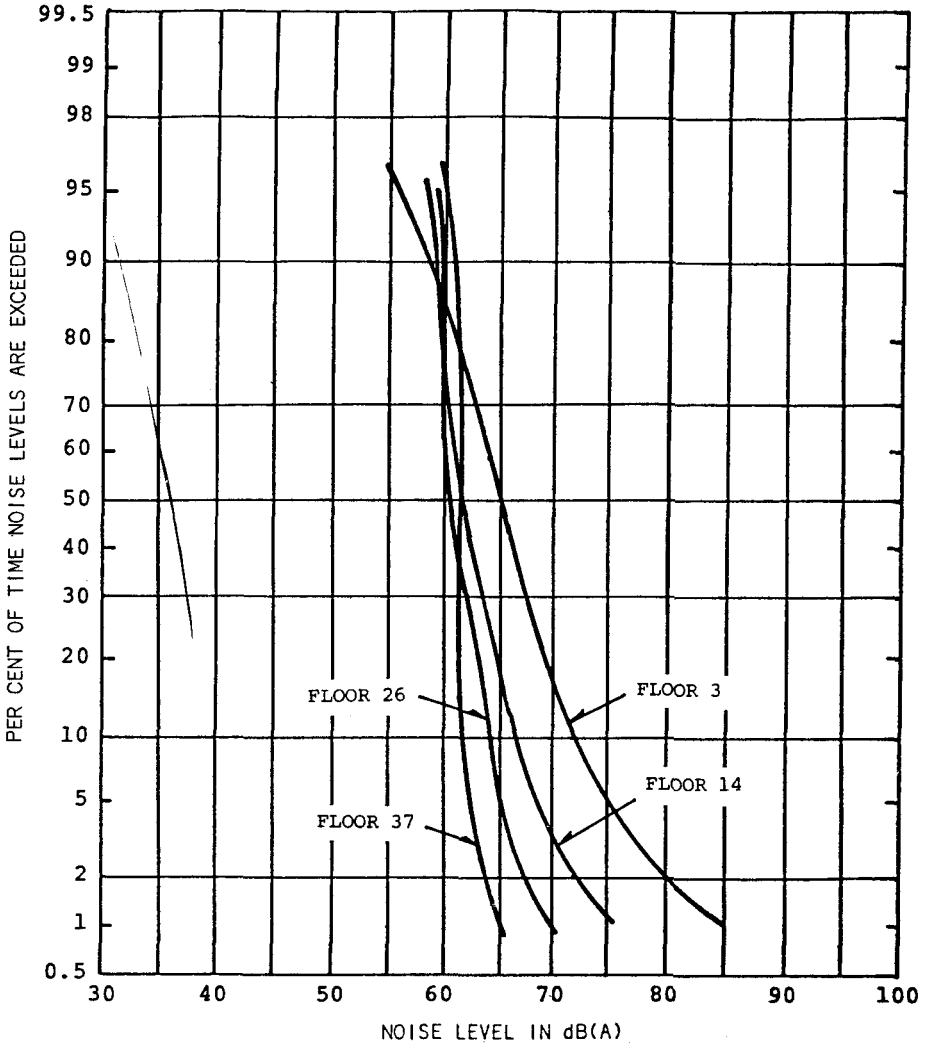
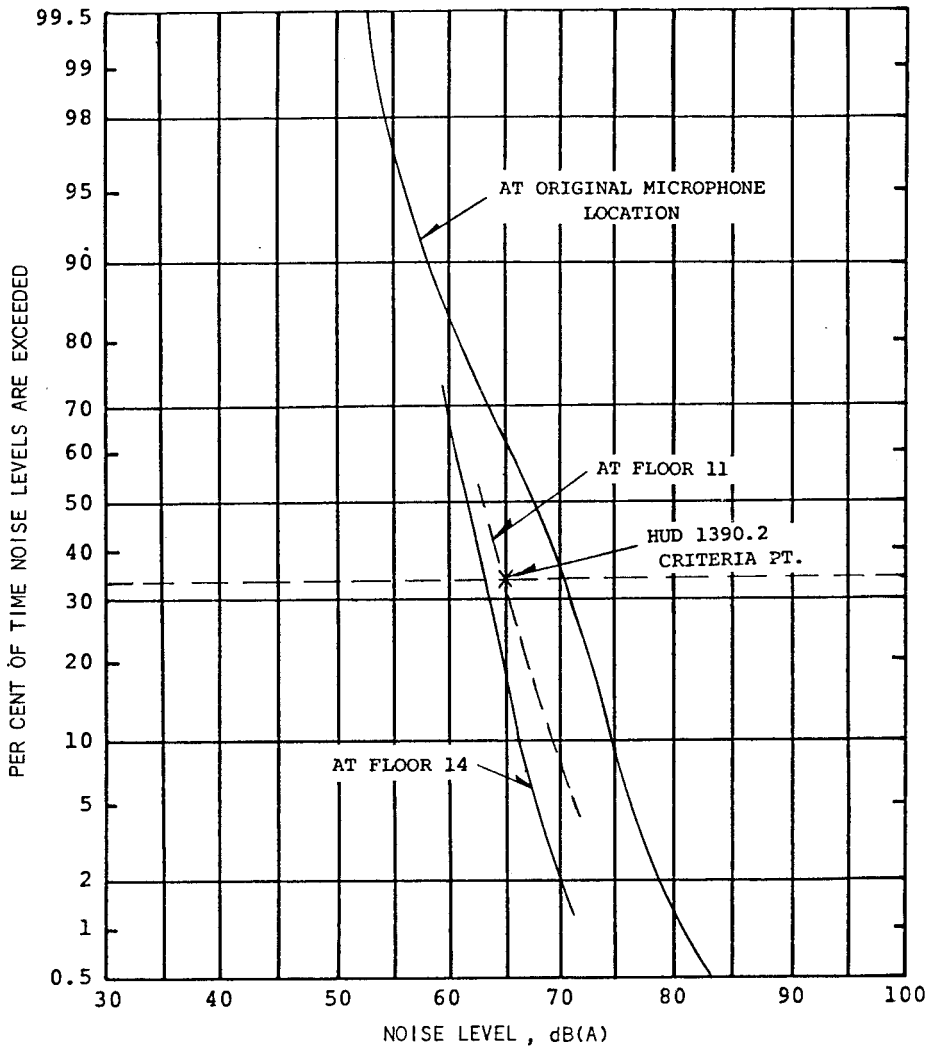


Figure 7.—Interpolation between exceedance curves for the tower floors establishes the approximate floor just meeting the Discretionary-Normally Acceptable criteria.



taken every half-second of the recording period and accumulated in 5-dB steps (pentads). The results, normalized to remove minor variations (fig. 6), showed a distinct convergence of the exceedance curves. For the 37th floor, the curve indicated a relatively uniform noise level approaching an L_{90}, A-weight, residual value of approximately 61 dBA. At floor 3, the full impact of local avenue traffic was experienced, with wider excursions of noise level. The intermediate floors, 14 and 26, indicated a relatively lower influence of immediately local traffic noise.

Transposition of the elevation adjustment to the original normal traffic noise base permitted an interpolation approximating the tower floor that would have an exceedance curve (fig. 7) to the right of the discretionary transition point. This was computed to be floor 11. Mitigating measures were indicated as recommended for residential floors 2

through 11 on the avenue side of the tower and all six residential floors of the avenue side of the building wing.

Sutherland *(1975)* has reported a recorded A-weight residual level ranging from 69 dBA to 73 dBA from ground level to 20 floors above ground level at another high-rise apartment site in New York City. For the particular study made by Sutherland, his L_{90} residual levels were materially higher than those recorded during this investigation since the nature of the local and distributed sources of noise were different. However, a similar flat L_{90} relationship was found when the L_{90} A-weight levels were plotted as a function of the various floor heights above ground.

An additional series of tests were performed at each of the test floors. A bedroom window on each test floor was opened so that the open area was 5 percent of the floor area of the room, essentially complying with the New York City building code minimum requirement for adequate ventilation. Microphones were set up in the center of the rooms and directly outside on the 1-meter booms. In each case, when the window was open, the room level was 12 dBA greater than when it was shut. The windows were conventional Alwinseal double hung sash with DSB (⅛-inch) glass.

On the side street, along the L-wing of the building, the effect of avenue noise was determined by locating microphones exterior to rooms e, f, and g (fig. 8) located on the 5th floor of the wing. Simultaneous recordings were made only during intervals when no traffic moved on the side street and with active traffic motion on the avenue. The noise level distribution at the test locations in terms of statistically accumulated pentad samples (fig. 9) shows a con-

Figure 8.—Section view through tower and L-wing showing apartment and room locations and the designation of measurement rooms (a, b, c, d, e, f, g).

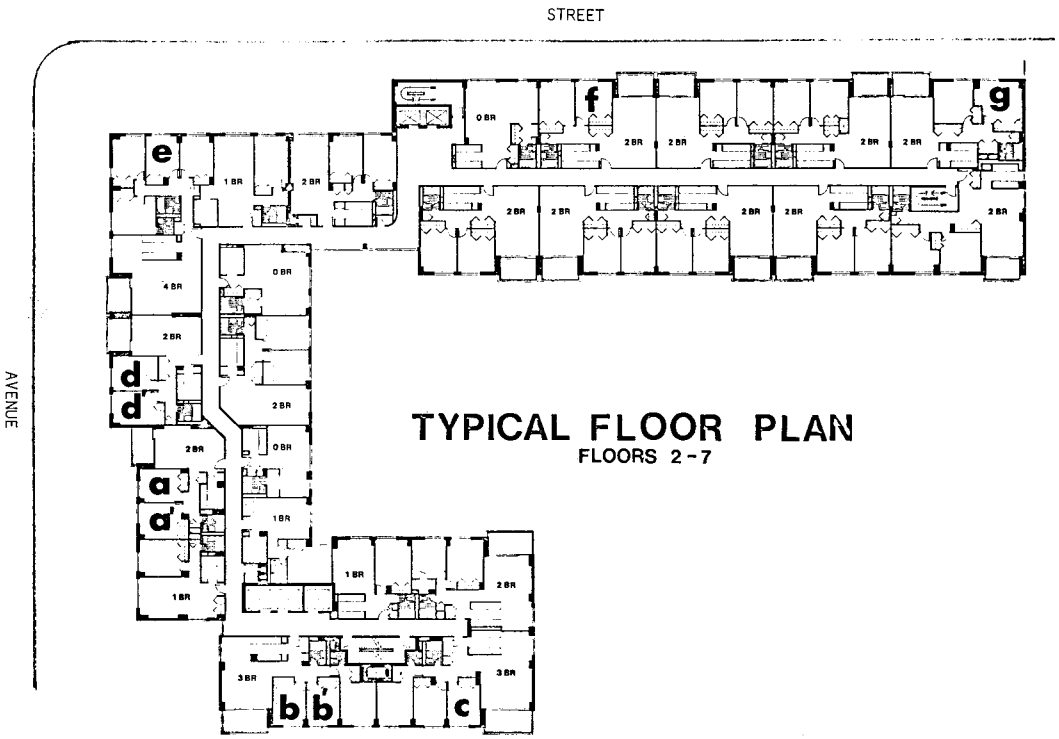
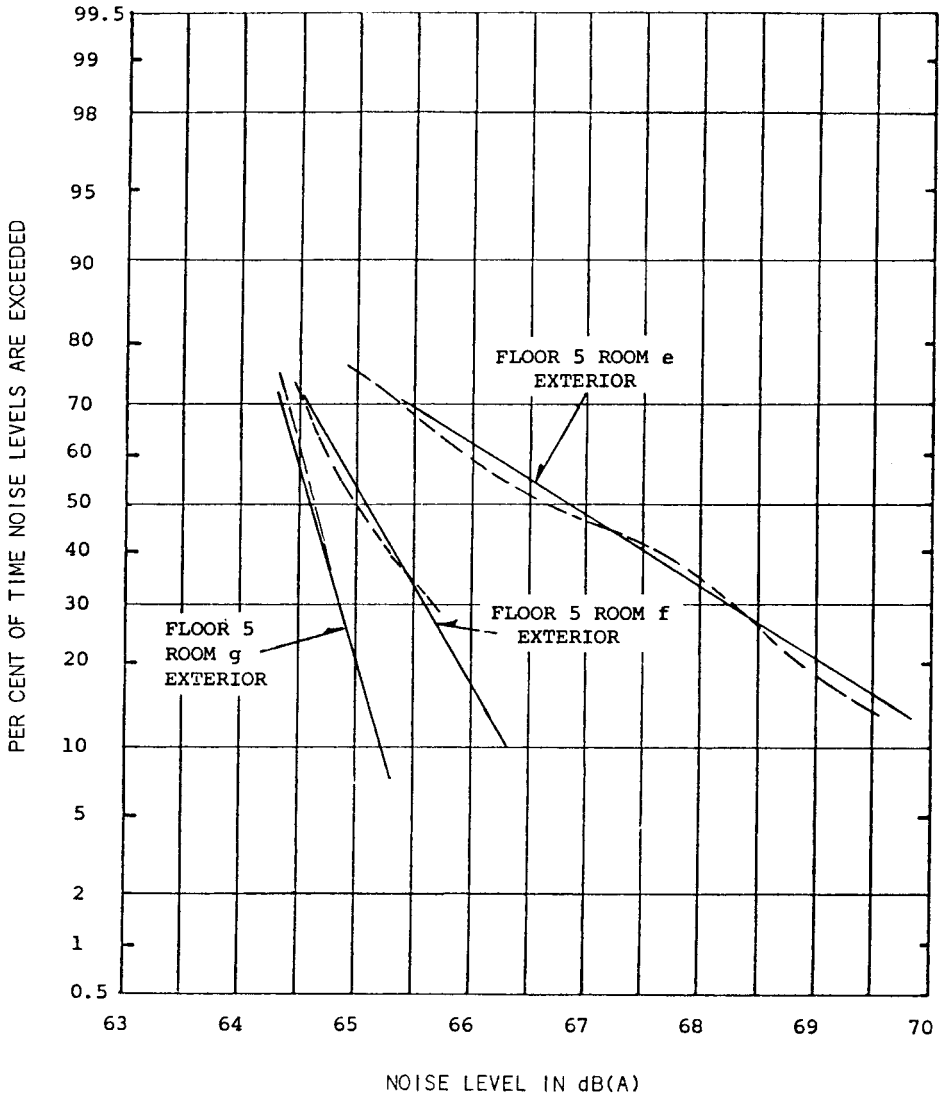


Figure 9.—Statistical exceedance distribution of recorded exterior noise levels along the street side of the L-wing at three widely separated locations. Noise is primarily from avenue traffic, with no moving traffic on fronting street.



verging pattern, the remote location exhibiting the lowest and smoothest characteristic.

Much work remains to define in depth the effect of vehicular traffic noise on high-rise structures with respect to local and distributed sources as an aid for planning and architectural design.

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Community Noise Monitoring Program

by ARNOLD G. KONHEIM, *Office of Noise Abatement and Control, U. S. Environmental Protection Agency, Washington, D. C.*

ABSTRACT.—There are numerous questions in regard to methods, instrumentation, and human and agency resources for community noise monitoring. The U. S. Environmental Protection Agency is currently in the process of seeking answers to these questions through research within the agency and by cooperation with other organizations, including the Department of Defense and the National Bureau of Standards. EPA hopes to have an acceptable protocol for community noise monitoring by July 1977, but there will still exist a long-term requirement for developing more meaningful and efficient techniques.

LISTENING TO MY COLLEAGUES who preceded me, one might infer that environmental noise monitoring is such a well-explored field that its challenges lie only within deep acoustic crevices. I am sure that they would be the first to admit that this is not the case.

At EPA, we are asking some basic questions concerning noise monitoring, and it is to this phase of our activity that my remarks are addressed. It is hoped that the considerations raised here will contribute to this conference in the following manner:

1. By familiarizing you with the problems of community noise-monitoring.
2. By encouraging greater participation in the search for solutions to these problems.

WHY MONITOR?

EPA is currently in the midst of developing an environmental noise-monitoring and assessment program to satisfy the following needs:

1. Develop an environmental noise baseline to asses future trends.
2. Identify populations at risk in terms of public health and welfare from the standpoint of exposure to noise sources and mixes.
3. Establish standard methods to assure quality assurance in the area of data collection and processing.
4. Provide technical assistance to state and local governments in the characterization of their environments.
5. Collect noise data to support EPA's standards and regulatory activities.

To meet these needs we are in the process of developing a protocol to answer three basic questions:

1. How shall we monitor (i.e., what is our methodology)?
2. What are our instrumentation requirements?
3. What are our resource requirements?

We are committed to seeking answers to all three questions. However, as this program is only in its initial stages, emphasis has been placed on solving the first two questions.

APPROACH

One can categorize monitoring in several ways. A first breakdown might be to separate an assessment based upon the physical collection of data from that based upon a social or attitudinal approach. Monitoring can also be looked at in terms of focus. Are we seeking to obtain an integrated community measurement, merely examine specific sources, or determine the exposure ex-

perienced by persons of different lifestyle's throughout their daily activities?

Based upon the above, it appears that one can investigate six combinations of monitoring approaches; in fact, these reduce to three. All of the social techniques are based upon interviews with community residents: only the questions vary. Physical personal monitoring is effected by instrumenting an individual with a personal noise-exposure meter or dosimeter which he wears for a particular period. The other physical techniques, i.e. integrated community and source specific, consist of instrumenting the community. While we are approaching monitoring from all of these directions, I will direct my remarks only to the physical integrated community and physical source-specific measurements.

SPECIFIC AREAS OF INVESTIGATION

The first area of investigation is the methodology for data collection. We are seeking to find solutions to the following questions:

1. How shall we temporally sample?
2. How shall we spatially sample?
3. To what extent and in what way is noise source identification important?
4. What must our monitoring system performance characteristics be?
5. To what extent do indoor and outdoor measurements correlate?

As part of a trend evidenced by instrumentation in general, noise-monitoring systems process data through a digital processing network. Digitization implies a sampling rate. Thus, our first concern, within the temporal domain, is determining a minimum sampling rate, for example 100 samples/s, 1 sample/s, or 0.1 sample/s. Looking at longer time periods, what should be our minimum daily sample (1 hour/day)? How do we treat cyclic and seasonal patterns?

Within the spatial domain, areas of concern are as follows;

1. By what techniques shall we sample (deterministic, stratified)?
2. What criteria shall be used for site selection?
3. How many sites must be selected for a particular criterion?
4. What are the effects of sampling at various heights?

In noise-source identification, what are the problems attendant to and the advantages of identifying sources through human observers, through microsampling, and through signal processing? What are the important output parameters (L_{eq}, L_{dn})? How do we relate indoor to outdoor measurements?

Another methodological area of concern is the processing and assessment of data. Just where is data to be processed and by what means? How can the data best be assessed to accomplish our program objectives, and how can it best be presented so that it is most meaningful to those people who must make decisions?

Our concerns with instrumentation are both systems- and component-oriented. With regards to the system, we are concerned with both its technical capabilities and its ability to perform under field conditions. Thus, we are concerned with such factors as security, weather, ability to withstand vibration, and operating at long periods of time without inspections. We are also concerned with components. What microphone system is suitable for use at long periods of time in the outdoor environment? What kind of windscreen shall be used with this? How can tape mechanisms and computers function in the outdoor environment?

We are concerned with obtaining nonacoustic as well as acoustic information. Nonacoustic data which may be useful are windspeed, temperature, humidity, source to microphone distances, and speeds of transportation sources. Although most monitoring approaches collect and perhaps even partially process information at the site, it is possible to

telemeter the information back to a central location. Is telemetry a viable approach; and if so, to what extent is it useful?

IMPLEMENTATION

Our basic philosophy in answering some of the questions that have been raised today has been to consider each of the areas separately with the intention of integrating these as we find solutions applicable to the various areas. To the maximum extent possible, we have limited our own research by applying the results gathered by other investigators. Using EPA regional and headquarters resources, we have field-tested methodologies and instrumentation systems while collecting data valuable to our agency as well as local communities. Our community monitoring has included cities ranging in size from Morgantown, W. Va, to New York City. In the area of monitoring source-specific areas, we investigated the noise associated with railroad yards and along rights-of-way. Presently, we are planning a construction-site monitoring program in which we will study all types and phases of construction activity.

Now let us review some of our approaches to obtaining solutions to these problem areas.

Most of the temporal analysis has been accomplished or is being accomplished through the multiple processing of analog tapes. In October 1974, utilizing our regional resources, we collected over 1,800 hours of digital data during the previously mentioned railroad monitoring. In addition, we gathered approximately 20 hours of analog recordings. We are now processing a selected group of these analog tapes to help us arrive at a proper temporal sampling plan. First, we are interested in determining the effect of various response times on sampling accuracy. Second, we are investigating the accuracy in deriving selected hourly statistics (for example, L_{eq}, L_1) for a range of sampling rates for 45-minute tape segments. Starting with the highest sampling rate (approximately 20 Hz), the rate will be lowered until the levels differ from the original baseline rate of approximately 5 dB. In order to determine the necessity for continuous monitoring, hourly statistics obtained in 5-minute intervals will be compared with that for the entire tape length. A study will be conducted on the effect of changing that point on the tape at which the sampling starts. Finally, the hourly statistics will be determined by using the linear A, C, and D weighting networks for railroad yard noise and train-pass noise to determine the extent to which low-frequency energy contributes to community noise.

Determining the optimal way to sample spatially appears to be a much more difficult problem. Two years ago, when we initiated the noise-monitoring program, we brought to EPA a panel of experts in noise monitoring for a one-day session where we discussed what constituted good monitoring procedures. The area in which we found the least agreement among those experts was on the approach to spatial sampling. Moreover, in fall 1974, at the meeting of the Acoustical Society of America, we presented a paper on spatial sampling. The first part of the investigation was dedicated to a review of previous community noise surveys. We studied these surveys with respect to the following criteria:

1. Number of sampling stages.
2. Sampling technique applied by stage.
3. Spatial criteria used by stage.
4. Total sampling area.
5. Survey length.
6. Total number of measurement sites.
7. Length of measurements made per site.
8. Number of equipment systems and the survey objectives.

We found that there were nearly as many sampling procedures employed as there have been studies performed. Ow-

ing to the variability in objectives and other parameters of community noise surveys, it appears that no single sampling procedure is optimal for all community noise surveys. There is a need for a statistical analysis of the relationships of the various proposed spatial criteria to sound descriptors. What we are asking is: which criteria are necessary for characterizing spatial changes in community noise?

We are about to begin an analysis of previously collected data to answer this question. It is intended through application of our regional resources that we can further determine the number of sites per criterion by implementing a program of multiple site monitoring. In the area of three dimensional sampling — i.e., looking at height variations — we have just completed a noise survey at the Crystal City area of Arlington, Va., in which we located monitors above the top of an 11-story building and in various locations on the ground to determine if we can integrate spatially by measuring from above the area. In addition, our regional office in Denver, Colo., has been investigating aerial noise sampling from a balloon suspended approximately 1,300 feet above Boulder, Colo.

Until now, we have hired college students to act as observers so that we might have a record of what noise sources predominated during a monitoring interval. We are, however, looking at other approaches to noise-source identification. We recently purchased microsampling systems to operate in conjunction with our all digital noise-monitoring systems so that we might be able (through time compression) to derive noise-source identification information. Recently we initiated programs to test feasibility of signal processing as a mechanism for noise-source identification. We are looking at techniques such as cross-correlation, which have been used to distinguish among various noise-source generators. Most of the technology for this was developed by the Department of Defense. We are now asking the question: can this technology be transferred at a reasonable cost?

Presently, the U. S. Army's Construction Engineering Research Laboratory is evaluating noise-monitoring systems for us in the field and in the laboratory. We expect the results to be completed within the next month.

The National Bureau of Standards is currently investigating various microphones for application to outdoor noise monitoring. These include condenser, electret, and ceramic microphones, which are being evaluated as a function of temperature (—20° to +50°C) humidity (25 to 95 percent) and frequency (100 to 5,000 Hz). The actual acoustics tests have been completed. NBS will now perform a cost analysis before preparing a final report. In cooperation with the Navy, we are studying the application of telemetry to environmental noise monitoring. Low-cost telemetry and sensor units developed by the Department of Defense show great promise, particularly for systems in which only limited information is brought (e.g., threshold detection).

Another concern is, where shall we process data? We intend to tackle this through an operations-research study scheduled to begin this fall, after which we will concentrate on data assessment and data presentation.

CONCLUSION

While we hope to have answered many of these questions to the point that an acceptable protocol will have evolved by July 1976, there is a long-term requirement for developing more meaningful and more cost-effective techniques.

The multitude of problems we face requires the skills of many disciplines: scientists, engineers, environmentalists, urban planners, social scientists, and statisticians. It is an exciting field. I encourage your participation.

Sound Absorption Characteristics of Tree Bark and Forest Floor

by G. REETHOF, O. H. McDANIEL, *and* G. M. HEISLER, *respectively professor and research assistant, Noise Control Laboratory, The Pennsylvania State University, University Park, Pa.; and research forest meteorologist, USDA Forest Service, Northeastern Forest Experiment Station, Pennington, N. J.* *This research was supported by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Studies.*

ABSTRACT.—Results of basic research on absorption of sound by tree bark and forest floors are presented. Amount of sound absorption by tree bark was determined by laboratory experiments with bark samples in a standing-wave tube. A modified portable standing-wave tube was used to measure absorption of sound by forest floors with different moisture contents, with and without leaf litter, and with and without moss growth. The implications of the results are discussed in terms of the amount and mechanisms of sound absorption by entire forests.

PLANTINGS OF TREES and shrubs of sufficient density and depth are well known to reduce some highway and industrial noise. The pioneering work of Eyring *(1946)* and subsequent work by Wiener and Keast *(1959)*, Embleton *(1963)*, Aylor *(1972)*, Cook and Van Haverbeke *(1971)*, and Reethof *(1972)* generally showed that attenuation of noise by forests depends on four factors:

1. Forest density.
2. Forest depth.
3. Frequency of noise radiated by the source.
4. Micrometeorological factors such as temperature gradients and to some extent wind velocity and vertical wind profile (wind is significant only if large distances between source and receiver exist).

The attenuation of noise by forests is usually expressed by the terrain loss coefficient, which is the acoustic transmission loss between any two specified points, x_2 and x_1, in the forest corrected for spherical divergence and divided by the distance $x_2 - x_1$. The terrain loss coefficient is, therefore, the transmission loss per unit of forest depth.

The results obtained by several investigators are given in figure 1, which is a plot of terrain loss as a function of source octave band frequency. The research was done in natural forests typical of the northeastern United States, which contained considerable rhododendron or mountain laurel in the understory. The important fact is the low absorption at frequencies up to about 500 Hz, with marked increases in absorption with increasing frequency above 500 Hz. Typical truck and automobile noise spectra are fairly flat, with peaks in the 125-Hz octave band (fig. 2). We conclude, therefore, that several hundred feet of forest are required to provide significant reductions in the A-weighted sound levels from vehicular traffic.

The mechanisms of noise propagation and attenuation in forests is complex. Consider a sound wave of, for example, 1000 Hz frequency (with a wavelength of about 1 foot) entering a forest. The tree trunks with diameters comparable to the wavelength will partially reflect and slightly refract the incident wave. This process is called scattering. The low-frequency waves (wavelength large compared to trunks and branches) will

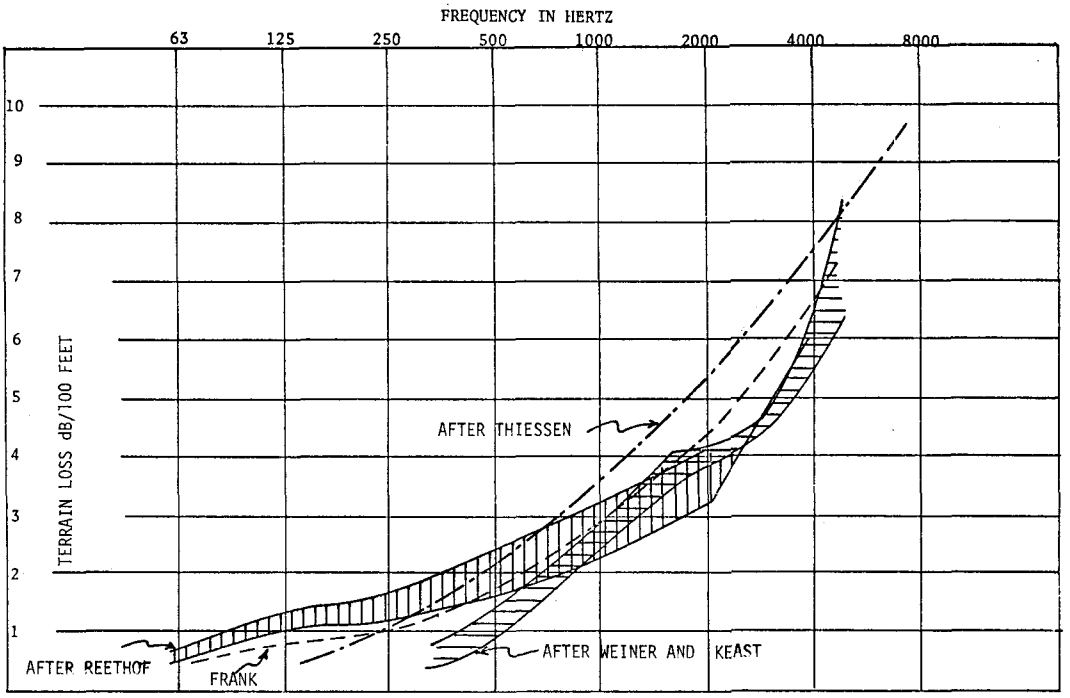
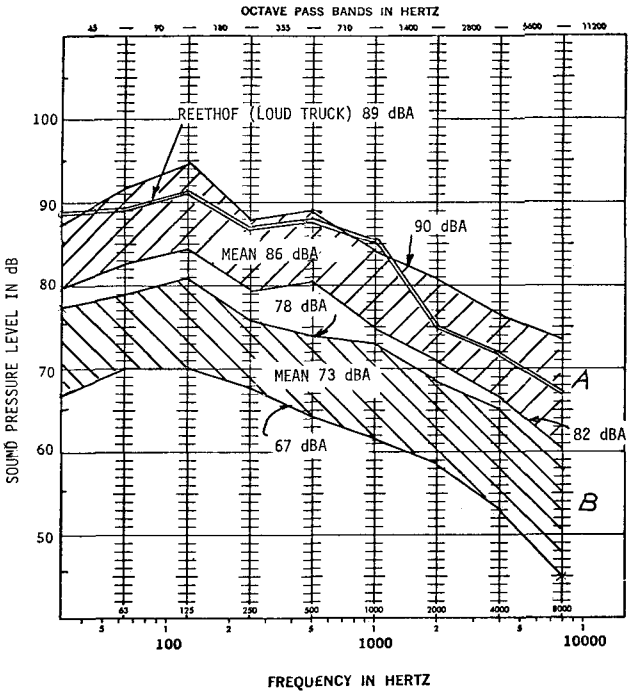


Figure 1.—Terrain loss of typical forests in northeastern United States and eastern Canada as a function of noise frequency *(Frank 1971 and Thiessen 1969).*

Figure 2.—Octave-band spectra for vehicular traffic.



A--Trucks

B--Passenger Automobiles

be transmitted almost unaffected by this phenomenon, whereas the high frequencies (> 1000 Hz) will be increasingly scattered with increasing frequency. This means that, with increasing frequency, the transmission paths will become increasingly complex and longer, providing greater opportunities for acoustic energy absorption to take place. Aylor *(1972)* has shown theoretically and experimentally that canopies, branches, and stems should be expected to provide some acoustic energy absorption as a result of viscous damping and thermal excitation. This phenomenon should be effective primarily at high frequencies.

At maturity, trees such as white oak *(Quercus alba)*, black gum *(Nyssa sylvatica)*, eastern hemlock *(Tsuga canadensis)*, and eastern white pine *(Pinus strobus)* have thick layered bark with considerable porosity. The possibility of absorption of substantial acoustic energy by bark in the multiple--scattering process should, therefore, be explored. In this paper we report some results of a study of normal incidence absorption by tree bark.

The effect of the ground is twofold. First, there is acoustic interference between the ground-reflected wave and the direct wave from a coherent source some distance above the ground. This "cancellation" is caused by the fact that the ground-reflected wave has to travel a longer distance than the direct wave, so that there will be a location at a certain distance from the source where the two waves are exactly at opposite phases, thus bucking one another. Acousticians will also recognize that because of the porosity of the ground, the reflected wave, as it leaves the ground, will be at a somewhat different phase than the incident wave at the ground surface.

The second effect of the forest floor is that it is a good absorber of sound because of its porosity. Typical forest-floor surfaces contain much decayed plant matter such as leaves, needles, branches, decayed trunks, and loose soil. Aylor *(1972)* performed grazing-incidence tests on open fields of unplowed, plowed, and disked soils. An excess attenuation of 6 dB per doubling of distance was shown to be possible. To study forest-floor absorption characteristics under more closely controlled acoustic conditions, we performed normal-incidence absorption tests, which will be reported here.

In all, the acoustics of forests are complex in that several forest elements affect the propagation processes in different and interacting ways. A study of the acoustic characteristics of the individual elements of the forest such as bark, canopies, shrubs, and forest floor should provide needed insight into the acoustic absorption mechanisms. Such insight will then permit the cultivation of the most important elements to maximize acoustic absorption.

BARK AS A SOUND ABSORBER IN FORESTS

Normal (perpendicular) incidence absorption of tree bark was measured with a standard impedance tube, also known as a standing-wave tube, manufactured by Brüel & Kjaer Instruments, Inc. Cylindrical test samples were cut from slabs of tree boles, leaving the wood intact behind the bark. Six species were tested: northern red oak *(Quercus rubra)*, mockernut hickory *(Carya tomentosa)*, eastern white pine, American beech *(Fagus grandifolia)*, eastern hemlock, and a cork oak *(Quercus suber)*.

The standing-wave tube is used to determine the fraction of the incident acoustic energy absorbed by a material in order to compare the effectiveness of various materials as acoustic absorbers. The apparatus generates pure tone waves that travel down the tube and strike the sample. Part of the acoustic energy is absorbed within the material, then the remaining energy is reflected and travels back up the tube. The super-

position of the incident wave and the reflected wave establish a standing wave, which occurs as a result of the interaction of two waves of the same frequency traveling in opposite directions. The amplitude maxima and minima, measured from the standing wave, are used to calculate the absorption coefficient. A typical axial pressure pattern is shown in figure 3.

Figure 4 shows a schematic diagram of the apparatus. The sample holder is mounted at one end of the 10-cm diameter, 1-meter long impedance tube. A loudspeaker is mounted in a box at the other end of the tube. A frequency oscillator produces selected tones, and a frequency counter monitors the tone sent to the speaker to insure accuracy within $\pm$ 1 Hz. During operation, a $\frac{1}{8}$-inch diameter microphone probe tube is moved longitudinally and centrally into the impedance tube. The microphone, located in the movable carriage, monitors the magnitude of the sound pressure of the standing wave. The signal from the microphone goes through a preamplifier to an audio frequency spectrometer. The absorption coefficient is then read from a calibrated scale on the

Figure 3.—A typical axial pressure pattern of the standing wave in the impedance tube.

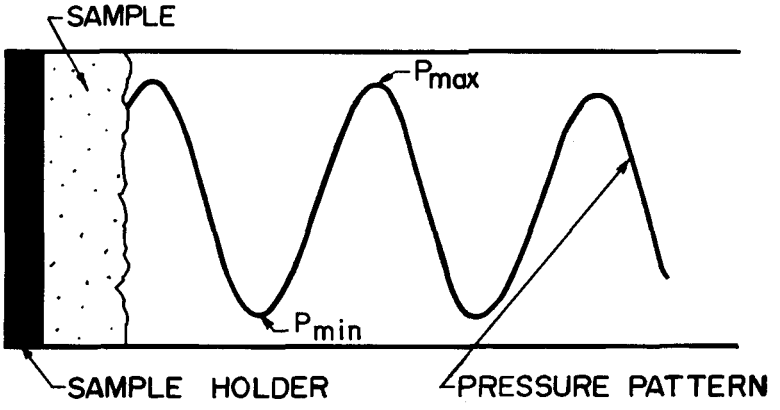


Figure 4.—Schematic diagram of the impedance tube apparatus.

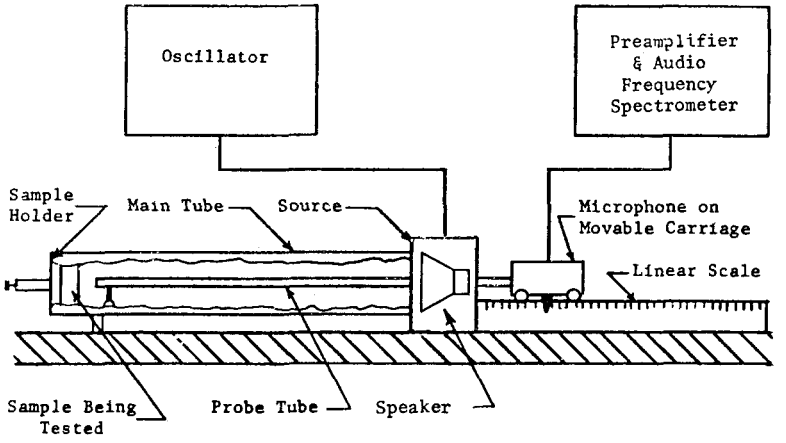


Figure 5.—Absorption of normal-incidence sound by bark of northern red oak.

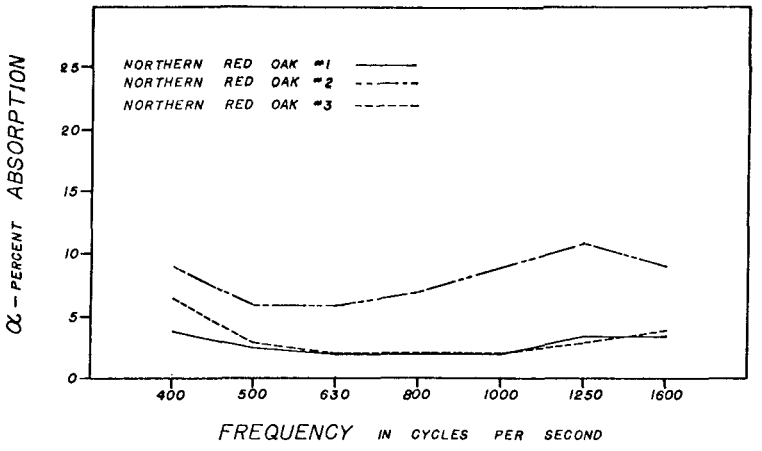


Figure 6.—Absorption of normal-incidence sound by bark of mockernut hickory.

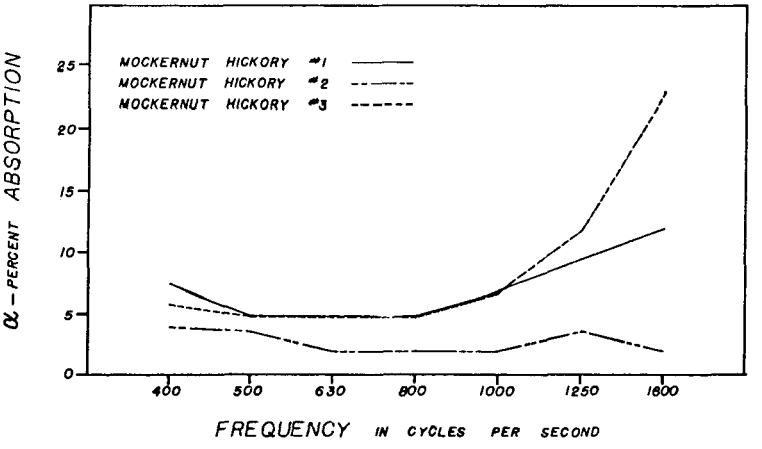
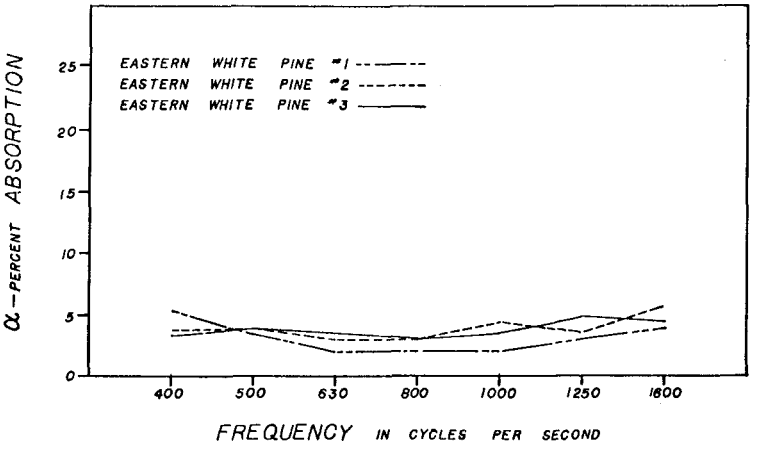


Figure 7.—Absorption of normal-incidence sound by bark of eastern white pine.



spectrometer. The samples were sealed in the holder by pouring paraffin between the sample cylindrical surface and the holder wall. It was determined that freshness of sample had no noticeable effect on the absorption coefficient.

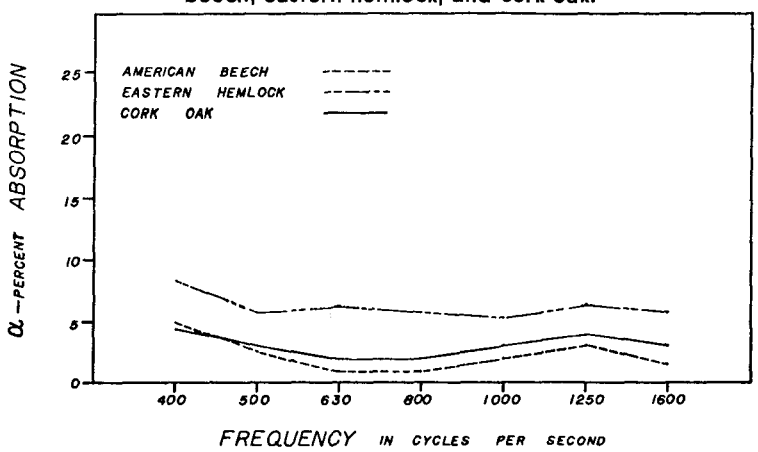
The 1-meter-long impedance tube is normally capable of providing reliable absorption data down to frequencies of 125 Hz. However, the presence of irregularities in the bark's surface made it advisable to record the maximum and minimum acoustic pressures at a greater distance away from the sample than otherwise possible during normal testing. This increased the lower limiting frequency, which depends on the length of the impedance tube available for measurement, to 400 Hz. The upper limiting frequency, which assures existence of plane waves, is determined by the diameter of the tube. Since sample surface irregularities do not affect the wave pattern far away from the sample, the upper limiting frequency of 1,600 Hz remained the same with the 10-cm-diameter tube.

The absorption coefficients versus frequency for samples of red oak, mockernut hickory, and white pine are plotted in figures 5, 6, and 7 respectively. Each figure shows the results for three samples, each checked for repeatability. The results of the repeated testing of each sample seldom deviated more than 1 percent. The absorption coefficients for all the samples of the three species was less than 10 percent, except for the hickory at frequencies above 1,250 Hz. One hickory sample absorbed a maximum of 12 percent, another 23 percent. The high absorption of mockernut hickory bark may be due to its shale-like layers with spaces between them. The spaces may allow vibration of the individual layers, and the air movement may result in acoustic absorption. This is a mechanical transformation of the incident acoustical energy, and most probably accounts for the additional absorption.

After the tests on oak, hickory, and white pine, we looked for bark characteristics that might alter absorption of sound and selected three other species for testing: American beech, eastern hemlock, and a cork oak (fig. 8). The hemlock sample had a higher absorption coefficient than the beech or cork oak, but all still indicated less than 10 percent absorption.

The percent absorption of the six

Figure 8.—Absorption of normal-incidence sound by American beech, eastern hemlock, and cork oak.



species we tested is quite low and largely independent of frequency. Although our six species provide a fairly wide representation of the characteristics of tree bark, tests on other species would certainly be warranted. Considering the small variation between species, it seems unlikely that any species would be found where the bark absorption would be so high that the sound attenuation of forests (or trees of that species) would be unique because of bark characteristics alone.

Although each tree surface may absorb only a small percentage of the incident wave, this effect is repeated as the sound wave is scattered towards the next tree, and so on repeatedly. The addition of the small absorption percentages is accumulative, yet we do not know how the total bark absorption will compare with that of the shrubs, foliage, branches, or the canopy as a whole. It can be assumed that the multiple-scattering principle will at least make the sound available to more surface area above the ground, since its path length is longer with each consecutive reflection. This gives the ground more chances at absorbing the scattered acoustic energy.

FOREST FLOORS AS A SOUND-ABSORBING SURFACE WITHIN A FOREST

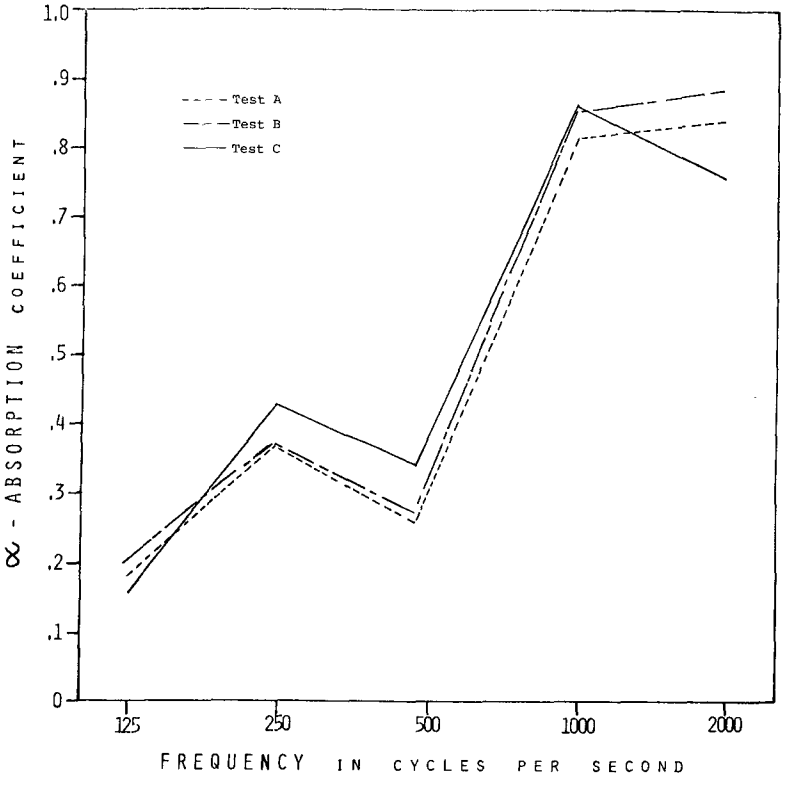
Normal incidence absorption of various forest floors was measured with a specially modified standing-wave tube that could be driven vertically into the ground without disturbing the soil within the 10-cm-diameter tube. The tube was 5½ feet long and permitted measurements in the frequency range of 125 to 2,000 Hz. The loudspeaker was located in a box mounted on top of the impedance tube. A frequency oscillator generated the pure tone sound signals. The ⅛-inch diameter microphone probe was moved longitudinally and centrally into the tube. The sound signals of various vertical locations of the probe inside the 10-cm tube were measured with an octave-band-filtered sound level meter. Again, the maxima and minima, were noted and the acoustic absorption coefficients were calculated. At the end of the five frequency measurements, the sample was ejected and another sample nearby was measurd to give an indication of the repeatability of the test.

All the field equipment is portable and battery operated. We used a four-wheel-drive vehicle to transport the equipment to various measurement sites within the forest.

To determine to what extent the various physical parameters of the soil (porosity, moisture content, surface configuration) will affect the measured absorption coefficient, each parameter was investigated separately. This was done by taking measurements with one parameter as the variable while all the others were held constant. The above was accomplished by noting the soil conditions at the time of the test and matching all but one of these conditions in the repeated testing. This procedure was adequate for determining the range of acoustic absorption controlled by each parameter with respect to the overall absorption of the sample. An analysis of this type of data leads to a better understanding of the mechanisms of absorption. The parameters exerting the most control or yielding the largest absorption variations are then identified quantitatively.

Figure 9 shows a typical curve of the absorption of a sample of the forest floor, the abscissa showing frequency in Hz and the ordinate showing the absorption coefficient α. The absorption shown here displays a primary peak (maximum value) at 1,000 Hz, a secondary peak at 250 Hz and a dip (low value) at 500 Hz. A particular forest-floor absorption curve can be compared to that of another location, in order to obtain an indication of the relative effectiveness of the floor as an absorber over the frequency range of interest.

Figure 9.—Absorption of normal-incidence sound by a forest floor—test for repeatability of measurements on one sample.



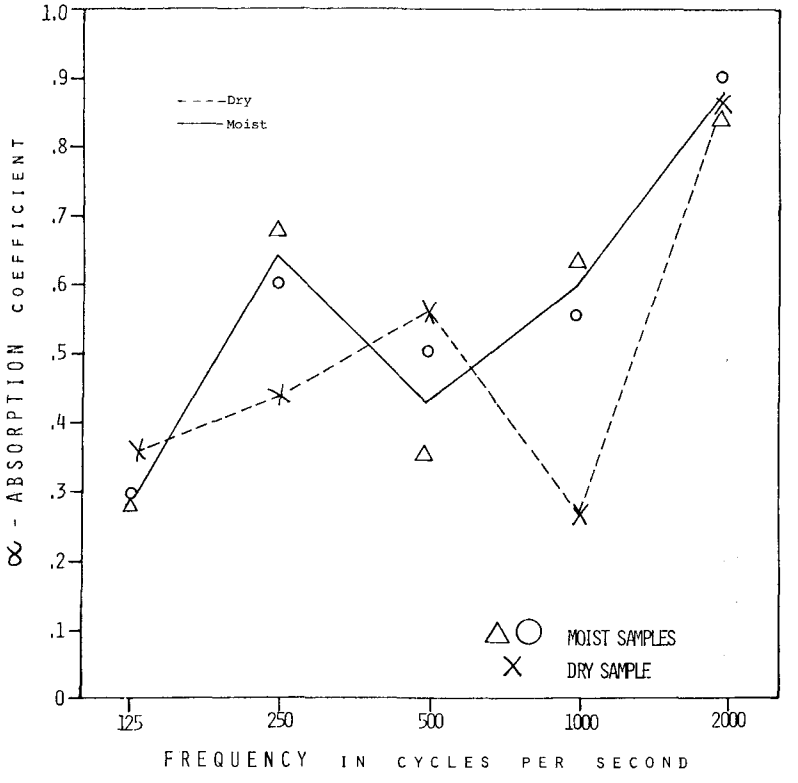
In figure 9, you can see that the three curves are nearly identical. This is the result of a test for repeatability of the same sample before its removal from the impedance tube. This variation is typical of acoustical measurements where data points within a few percent of each other are considered to be within the accepted range of tolerance. If there was a variation at a particular frequency of more than 0.05, the test was repeated before removal of the sample to confirm the results.

Each measurement condition was repeated by testing a comparable sample located approximately 2 feet away. This provides an indication of the variation between samples under the same conditions. The comparison of the absorption curves of either two or three measurements confirmed good repeatability for nearby tests.

A sample was tested when the ground was dry, without any rain for 2 weeks. The same locality was then retested when the ground was moist, 2 days after a heavy rain. The absorption curves for these tests are displayed together in figure 10. Since the sites were identical, we assume that all parameters remained constant except the moisture content of the soil. There is an indication from these two absorption curves that the ground was relatively more efficient at absorbing sound when it was moist than when it was dry.

An examination of several other sets of comparisons for identical localities with varying moisture conditions revealed some interesting trends. The sound absorption by the ground was noted immediately after rain; the amount of absorption increased after a couple of days of drying and then pro-

Figure 10.—Absorption of normal-incidence sound — same forest floor with two different moisture contents.



gressively decreased day by day as drying progressed. When the ground became saturated with the next rainfall, the cycle started over again. Thus, the time for maximized absorption was about 2 days after a rainfall.

The magnitude of the variations of acoustic absorption in the comparisons was, of course, frequency- and time-dependent, and the variations at some frequencies were much larger than at others. An overall increased or decreased absorption for the frequencies considered was the criterion for evaluation. An explanation for this observed phenomenon presumably is a change in the porosity of the ground as it becomes saturated with water. It is known that the porosity of an acoustically absorbent material is an important factor in the absorbing mechanism. These results indicate that the moisture content is a parameter to be considered in further investigation.

The determination of the effects of absorption by grass were measured in the manner just mentioned. Figure 11 shows the absorption curves of two samples, one of bare soil and the other with several inches of dry matted grass. As can be seen by comparison, the grass-covered sample provides more absorption and would attenuate noise more effectively. Other comparisons of similar sets of curves show the same results. It should be noted, however, that though the planting of grass would add some absorption to the environment, this might in turn affect the absorption by the soil. If the grass were to change the moisture content of the soil through its growth process, or through any changes in the irrigation of the forest floor, this change in moisture would affect the soil

Figure 11.—Absorption of normal-incidence sound for grass-covered and bare soil.

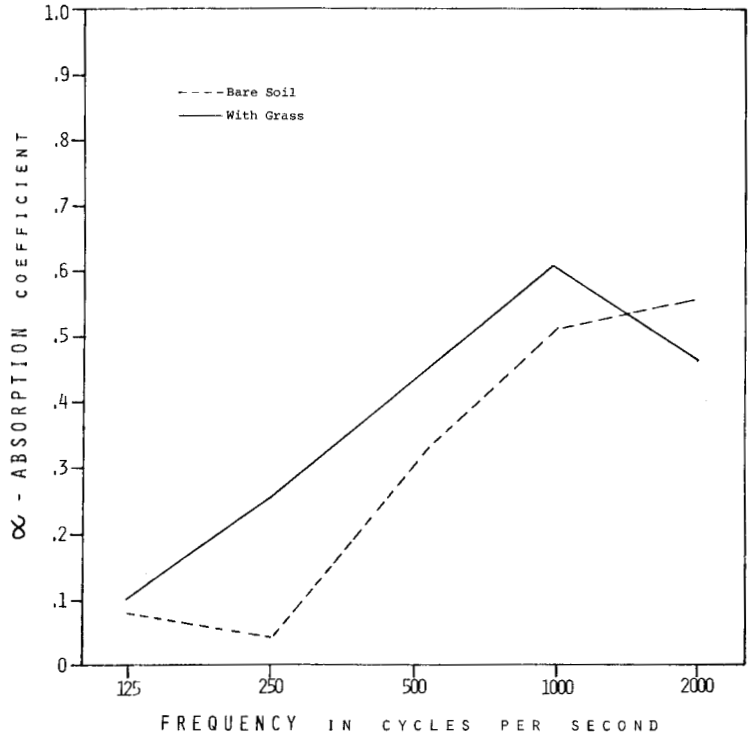
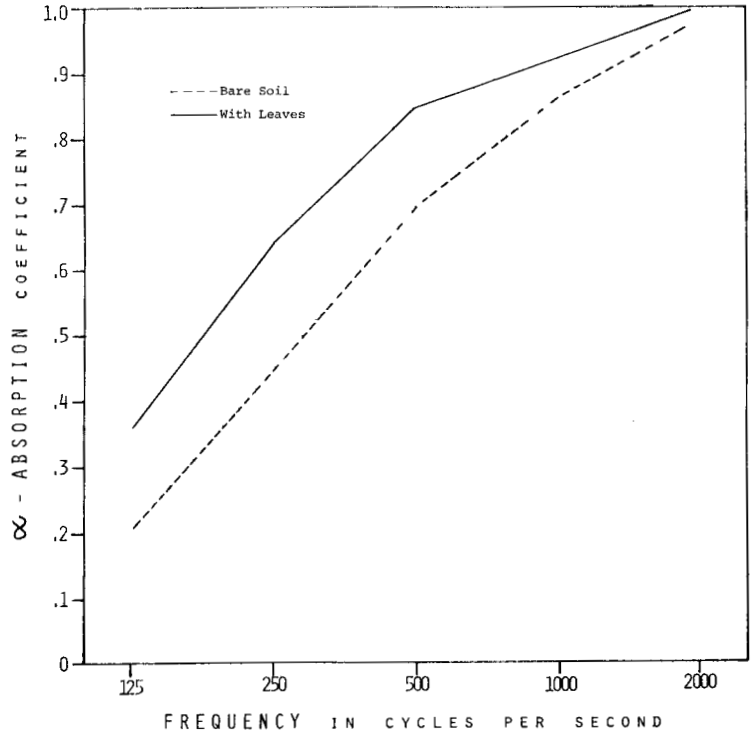


Figure 12.—Absorption of normal-incidence sound for soil with leaf litter and for the same soil without a litter layer.



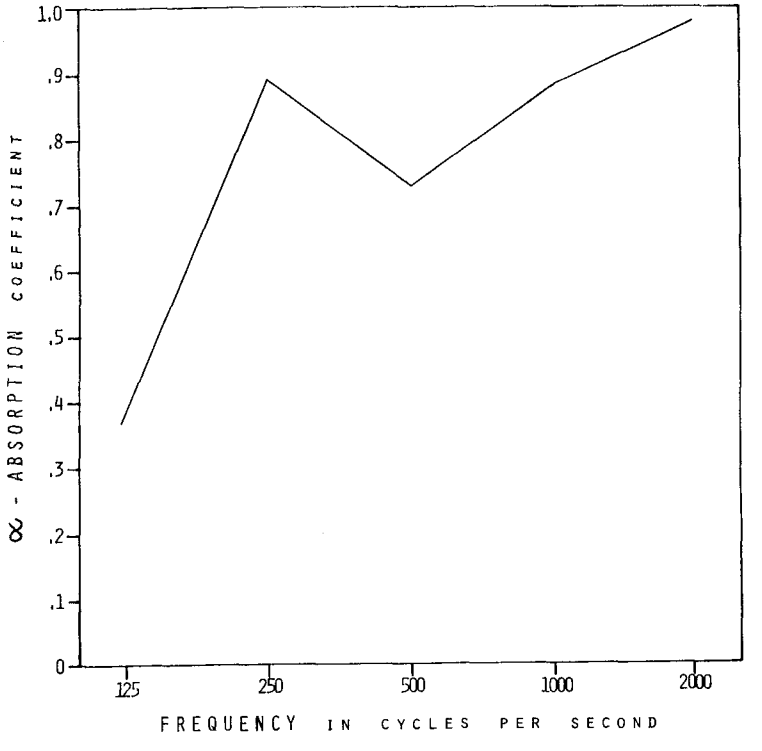
absorption. Whether or not this factor increases absorption has not been determined as of this time.

Similarly, the contribution of the absorption of the leaf layer in a deciduous forest was investigated. One such set of comparisons appears in figure 12. Like that of grass, the leaf layer adds to the absorption and in comparable amounts. Various isolated tests determined that the thickness and state of decay of the leaf layer were important factors. The comparisons of these tests show that, the thicker the layer of leaves present, the higher the percentage absorption obtained for a similar moisture content and thus the greater attenuation that would be provided. Similar tests were conducted in a coniferous forest with similar results.

In an attempt to investigate the absorption of the forest floor with a moss covering, the preceding method of testing a particular area with and without the vegetative covering did not give consistant or repeatable results. This may be due in part to the fact that the moisture content of the soil where moss grows is probably greater than that of nearby soil where there is no moss. Thus the inconsistancies would depend not only on the absorption by the moss, but also on the variations in absorption provided by different moisture contents of the soil underneath. Rather than a comparison in this case, the results can be summarized by stating that the absorption by a moss-covered ground is greater than that of bare soil or soil covered with leaves. A typical result can be seen in figure 13, a curve showing the absorption of moss-covered loam.

The results provide good indications of the normal incidence absorption characteristics of a typical forest floor. Forty-seven samples were tested, many of which were similar, providing indications of repeatability of the results.

Figure 13.—Absorption of normal-incidence sound by a moss-covered soil.



Some tests occurred with nonrepeatable results which we believe were caused by sample peculiarities. For example, a few samples were found to include rocks and roots. These samples were rejected from the analysis.

The question then arises, why forests do not attenuate sound to the magnitude that would be expected from all these results, as the percent absorption is quite high in some cases. This situation occurs because not all of the sound that passes through the forest actually comes in contact with the ground. Only those rays that strike the forest floor are partially absorbed by the ground. Here is where the trees become effective, as they act as sound scatterers, increasing the effective path length of each sound wave as it traverses through the forest. This gives the porous ground more chances to absorb the noise.

The results confirm that the ground is a significant absorber of sound in the forest. Moisture content and ground-cover structure have been found to cause variations in the absorption. The quantitative relationships of the effect of moisture, soil porosity, soil surface makeup, and extent of decomposition on absorption still need to be established.

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Acknowledgments. Leslie Frank made contributions to essentially all phases of this research, including equipment development and data collection and analysis. Formerly a graduate assistant at The Pennsylvania State University, he is now with Ostergaard Associates, Caldwell, N. J. Permission to use The Pennsylvania State Forests was obtained from the Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Forests. Assistance on location was provided by the A. D. Renninger Lumber Company of Richfield, Pennsylvania.

Evaluating Effects of Vegetation on the Acoustical Environment by Physical Scale-modeling

by RICHARD H. LYON, CHRISTOPHER N. BLAIR, *and* RICHARD G. DeJONG, *respectively professor of mechanical engineering, graduate student, and research assistant, Massachusetts Institute of Technology, Cambridge, Mass.* *The authors thank the National Science Foundation for its support under Project RANN in the development of modeling techniques used in this study.*

ABSTRACT.—It is generally assumed that vegetation is beneficial acoustically, as well as esthetically, in that it may act as a shield to reduce highway noise impact on a community as in a sound absorber to reduce reverberant noise levels in city streets. Contradictory evidence exists, however, that noise may be increased because of vegetation. We performed field studies and laboratory scale-model experiments to study interaction between sound-scattering by trees and shadowing by barriers. The studies indicate that, while barrier effectiveness may be reduced by addition of trees, propagation through a stand of trees may provide small noise reductions.

RECENT STUDIES of the behavior of vegetation placed on noise barriers have produced contradictory results. A report by Cann and Manning *(1974)*, based on model studies, suggests that trees placed on top of barriers can reduce barrier effectiveness, while field studies by Cook and Van Haverbeke *(1974)* show increased barrier effectiveness with trees. It was decided to use model studies to resolve this discrepancy.

Until recently, the use of scale models in acoustics has been limited to use in the design of concert halls and auditoria. However, within the past 6 years at MIT, modeling techniques have been successfully applied to problems in outdoor noise propagation by DeJong *(1974)* and Blair *(1975)*.

FIELD STUDIES

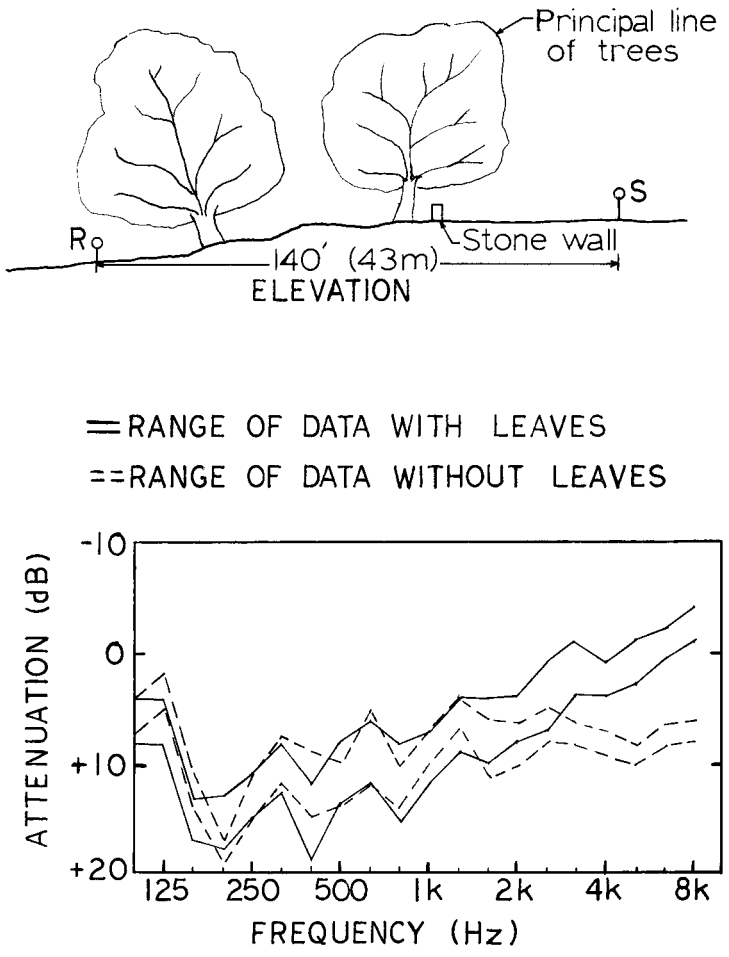
To evaluate the results of the planned model studies, it was necessary to conduct full-scale tests on vegetation configurations not fully covered in the literature, especially those in which the canopy is above the line of direct propagation.

The noise source used was a 12-gage shotgun, carefully studied for its noise spectrum characteristics. The pressure pulse was recorded on magnetic tape, using a Nagra tape recorder and a B&K 1-inch microphone.

Measurements were taken in late spring and early summer to assess the effects of the maple leaves. Care was taken to insure that ground conditions were similar on all measurement dates.

One of the sites chosen for propagation studies was a line of maple trees located at the top of a hill (fig. 1). Acoustic measurements were taken at various points beyond the tree line. Although there was a stone wall along the tree line, the tip of the shotgun muzzle was visible at all receiver points. An example of the measurements shows that the observed spectra with and without leaves begin to diverge above 2,500 Hz corresponding to a wavelength of about 5 inches (12.7 cm), approximating the tip-to-tip breadth of the leaves. The high-frequency excess attenuation observed with leafless trees may be attributed to backscatter from the trunks

Figure 1.—Excess attenuation in the sound propagating across a line of maple trees.

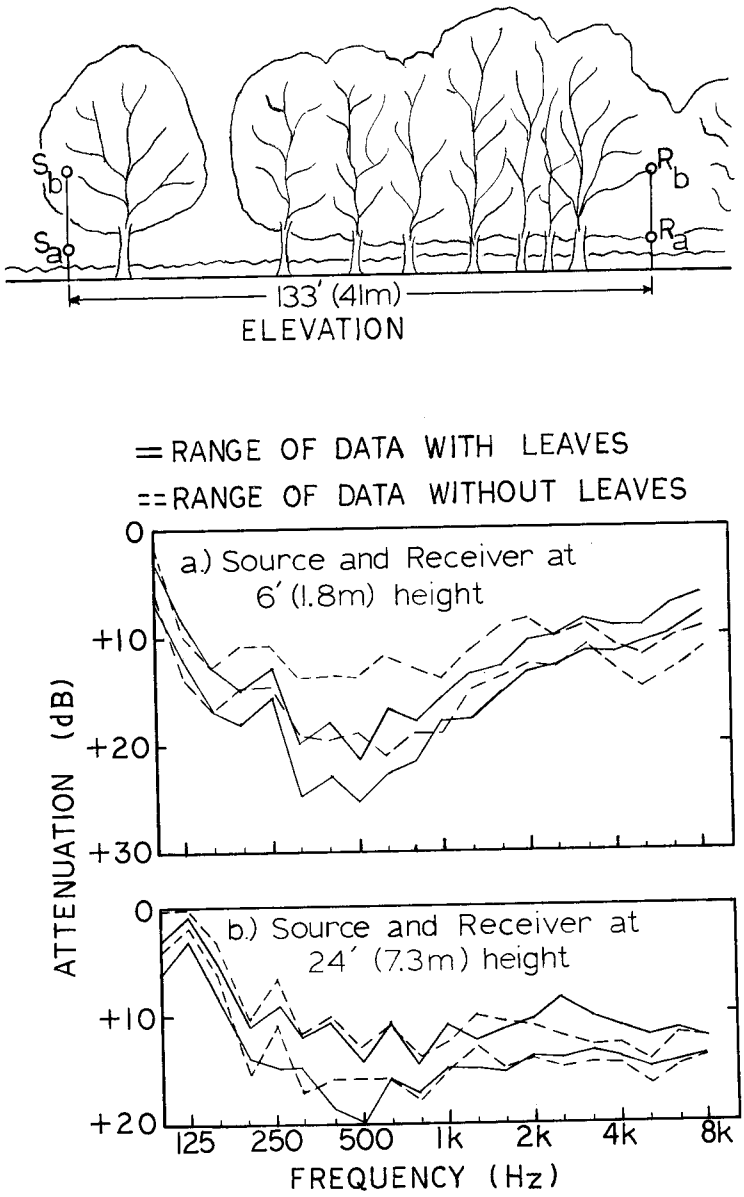


and branches and the effects of the stone wall almost intersecting the line of propagation.

The backscattering effects of trunks and branches were further studied in the following experiment. Sound propagation was measured along a line of trees at various heights in the canopy (fig. 2). Shotgun and microphone were suspended in the trees, and the line of sight was completely obscured by the trunks and branches. The large excess attenuations observed are due to backscattering from trunks and branches. At the position just below the canopy, leaves scatter some additional high-frequency sound to the microphone. In the canopy, however, leaves appear to have little effect. One may hypothesize that any additional attenuation offered by the leaves along the line of propagation is offset by scattering from leaves in other portions of the canopy.

In a third example of propagation under the canopy (fig. 3), shots were fired at various distances into a homogeneous mature maple stand and picked up by a microphone on the edge of the woods. At all times there was unobstructed visibility from source to receiver. As before, the leaves have a pronounced effect above 2,000 Hz, and

Figure 2.—Excess attenuation in the sound propagating through a canopy of maple trees.

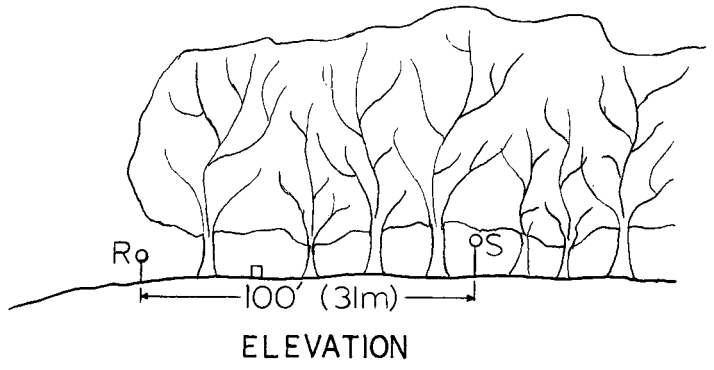


backscattering from the trunks of leafless trees results in high frequency attenuations. The large dip around 315 Hz is due to ground effect.

MODEL STUDIES

Model studies were then undertaken to facilitate more detailed studies of various tree-barrier configurations. Scale-modeling involves reducing all the dimensions in the system being studied by a scaling factor. Acoustical modeling requires that the wavelength of the sound be reduced by the same ratio as all other dimensions. This is most easily done by increasing the frequency of the sound used. Then, for example, in a 1:32 scale model, a full-scale frequency

Figure 3.—Excess attenuation in the sound propagating under a canopy of maple trees.



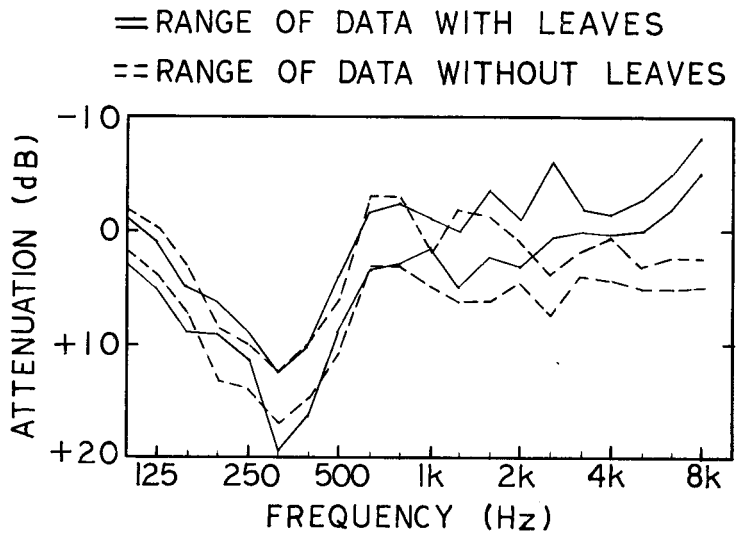
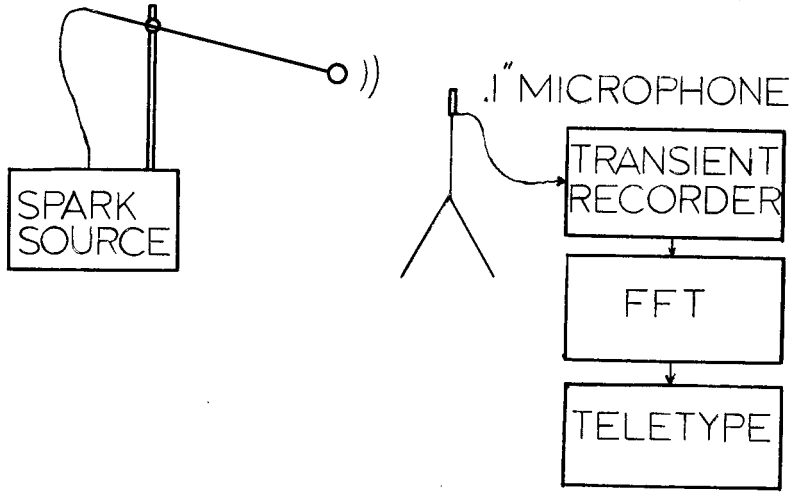


Figure 4.—Elements of the modeling system.



of 1,000 Hz would be modeled with 32 kHz.

To produce noise at these high frequencies, an electric spark discharge in air was used (fig. 4). Operating at 3,000 volts, this spark source produces an acoustic impulse with energy over a frequency range of 4 kHz to 150 kHz.

The sound was detected with a 1/10-inch piezoelectric microphone and recorded in a digital transient recorder. The recorder was interfaced with a digital computer, which performed a fast fourier transform (FFT) on the signal. The FFT values were then combined into a ⅓ octave band level and printed out on the teletype. These levels correspond to the levels that would be obtained using a steady state source in an anechoic chamber. However, by using an impulsive source, an anechoic chamber is not needed since the reflections off the walls arrive at the microphone after the desired signal is recorded. An oscilloscope was used to monitor the recorded signal to observe the arrival times of the pressure pulses at the microphone. This allowed the identification of different propagation paths from the source to the microphone.

The materials used in constructing the models were selected to have the same absorption at the scaled frequencies as the real materials being simulated have at audio frequency. The ground was modeled with a soft pressed fiberboard covered with flocked paper.

The model was constructed to a 1:20 scaling to allow analysis of full-scale frequencies as high as 5,000 Hz. Using trees actually encountered in the field studies as subjects, models were built representing 14-foot (4.3 m) pine and 30-foot (9.1 m) maple trees. Serpentine was used to model maple leaves; although it did not perfectly model leaf characteristics found in the field, the serpentine was determined adequate for qualitative analysis of leaf effects. Various leaf-area-per-unit-volume densities (F) could be modeled by changing the amount of serpentine placed in the canopy.

The basic experimental approach was to set up a line of trees in various configurations, with and without barriers, and measure the insertion loss of the vegetation at various distances behind the tree line. Results of excess attenuation across a line of model trees on a flat plain (fig. 5) are in good agreement with observed field data. Without leaves, the tree trunks appear to offer some attenuation above 1,000 Hz, but the presence of leaves scatters additional acoustic energy downward, resulting in reduced or even negative attenuation.

Next the attenuation of a barrier with and without trees on top was measured (fig. 6). In the case of the model maple trees, the scattering contribution of the

Figure 5.—Excess attenuation in the sound propagating across a line of model trees on a flat plain.

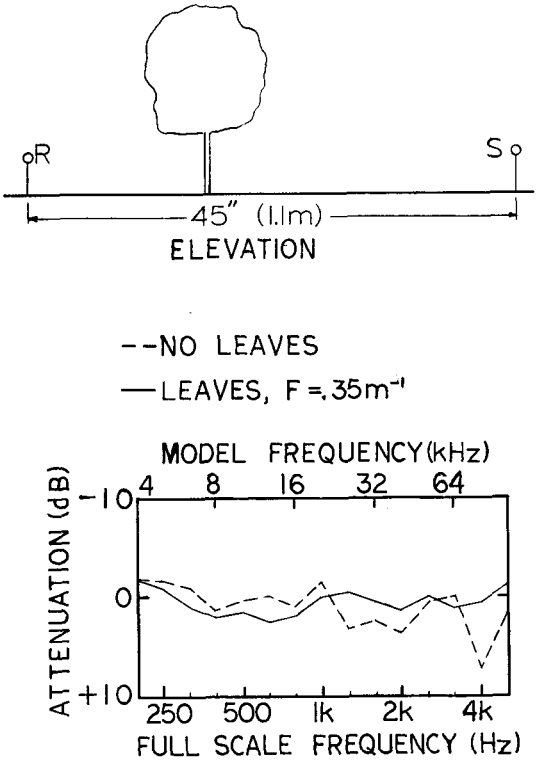
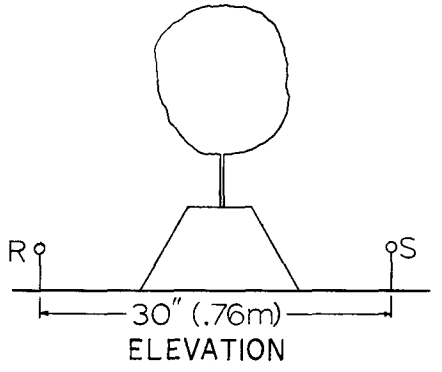
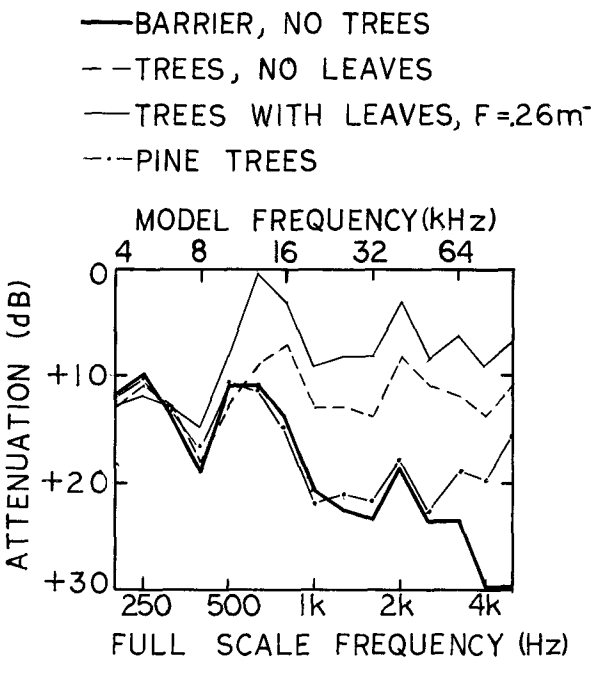


Figure 6.—Attenuation of sound by a barrier with and without trees on top.





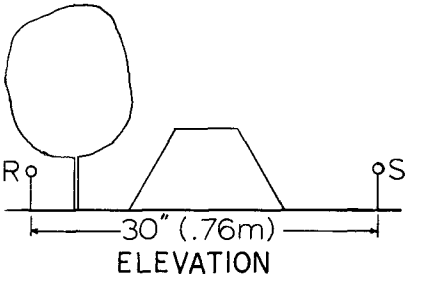
leaves occurs at a lower frequency than noted in the field data. This anomaly is due to the imperfect modeling characteristics of the serpentine, which is a long continuous tape rather than many small patches. The negative attenuation contributions of leafless maples are due to the scattering off of the major horizontal branches. The pines, which scatter sound at a higher frequency corresponding to the pine's smaller and more concentrated branches, display similar characteristics. As can be observed, planting a single row of trees on top of a barrier can be devastating to the barrier's effectiveness.

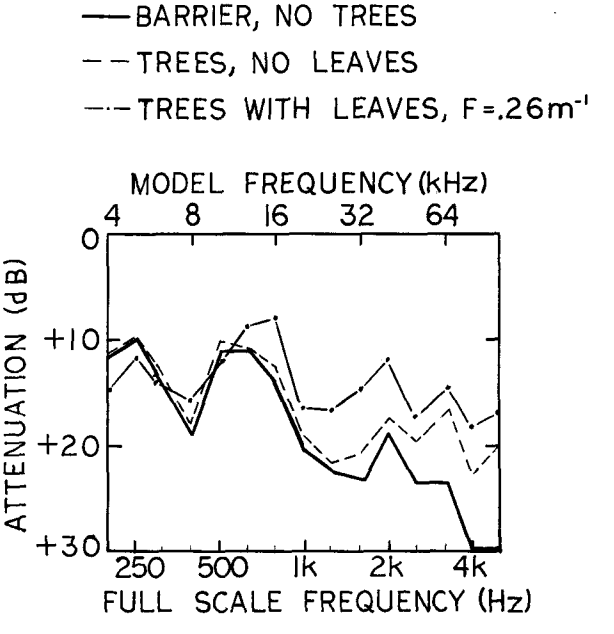
By moving the trees from the top of the barrier to behind it, the barrier effectiveness is not so severely damaged (fig. 7). Only about half of the canopy is exposed to direct sound from the noise source explaining this result.

DISCUSSION

The frequency dependence of the scattering effectiveness is consistent with dimensions of the scattering bodies: the smaller the leaf or branch, the higher

Figure 7.—Attenuation of sound by a barrier with and without trees along the side.





the frequency at which scattering becomes effective. Thus the presence of a plant with small branches and leaves will not appreciably affect noise levels in the frequency range of primary interest in noise-control circles.

Plant geometry also appears to be important. A tree with vertically hanging leaves and few horizontal branches, placed on top of a barrier, will scatter less sound downward into the shadow zone behind the barrier than other tree configurations.

The effects of the introduction of vegetation on the sound field beyond it can be generalized graphically (fig. 8). The leaves and branches scatter a portion of the incident acoustic energy to the side and backwards, resulting in a shadow zone behind the vegetation.

The introduction of a solid barrier between source and receiver complicates the analysis somewhat. The leaves and branches of the tree may now be considered as noise sources, and any portion of the canopy not shielded from the receiver will reduce the barrier's effectiveness through scattering.

However, if the barrier extends upward into the shadow zone behind the tree (fig. 9) another counteracting mechanism becomes important. The

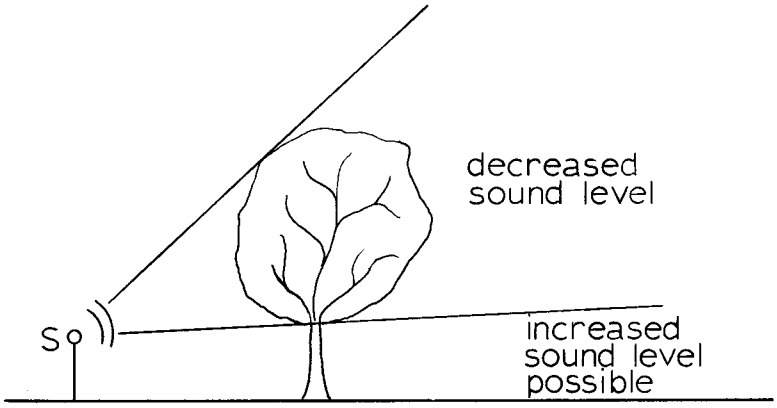


Figure 8.—The screening of sound by vegetation.

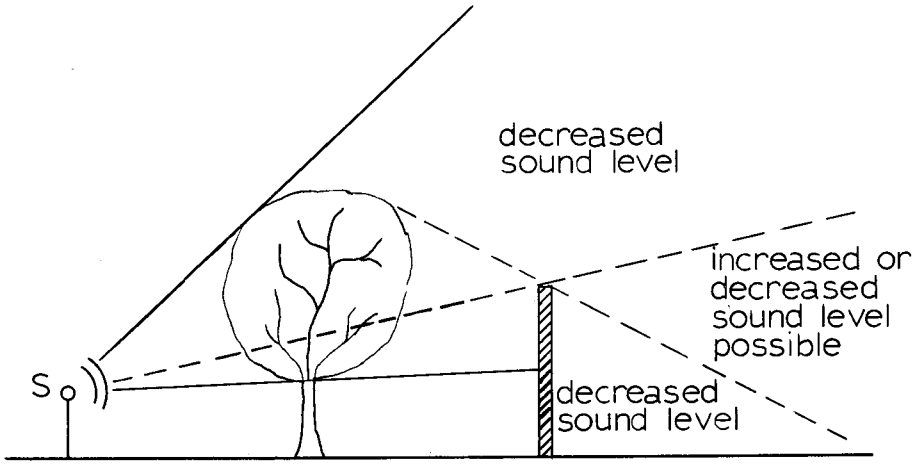


Figure 9.—Effects of vegetation upon barrier performance.

noise observed at the receiver point is dependent on the sound-field conditions above the barrier. If this sound field is reduced in intensity due to screening effects of the tree, barrier effectiveness is increased. Estimation of these scattering and screening components is essential in predicting the behavior of tree and barrier configurations. Since theoretical calculations are complex, this is best done by using model studies.

CONCLUSIONS

The results of this report show that scale-modeling can be a useful tool in evaluating the effects of vegetation on the acoustic environment. In particular, the positioning of trees around a barrier has an important influence on the barrier's effectiveness. Further work is being done at MIT to develop a simplified modeling-instrumentation system to facilitate the general use of modeling for the evaluation of a wide range of community noise problems.

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Propagation of Noise over and through a Forest Stand

by LEE P. HERRINGTON *and* C. BROCK, *respectively professor of meteorology and research assistant, College of Environmental Science and Forestry, State University of New York, Syracuse, N.Y.*
This research was supported in part by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Studies.

ABSTRACT.—Measurements of the two-dimensional acoustic field in a forest resulting from a source located outside the forest indicated that the attenuation pattern near the ground is significantly different from the pattern higher up in the forest. The patterns of attenuation support the recent theory that the forest floor is the main absorber of acoustic energy in the forest.

SOUND RADIATING from a point source decreases in sound pressure level (SPL) 6 dB for each doubling of distance due to spherical spreading of the wave front. Any additional reduction in SPL due to the presence of ground, vegetation, buildings, etc. is usually referred to as excess attenuation.

Measurements of excess attenuation within 10 feet of the forest floor indicate that the reduction in SPL due to the presence of the forest is approximately 6 dB per 100 feet of forest *(Bjornson 1971, Herrington 1974, McLaughlin 1975)*. These same studies indicated that the variation in SPL near the forest floor was not characteristic of the acoustic field in the forest at higher levels. The objective of our study was to describe the acoustic field within and over a forest stand in a vertical plane parallel to the propagation of sound from a point source.

METHOD

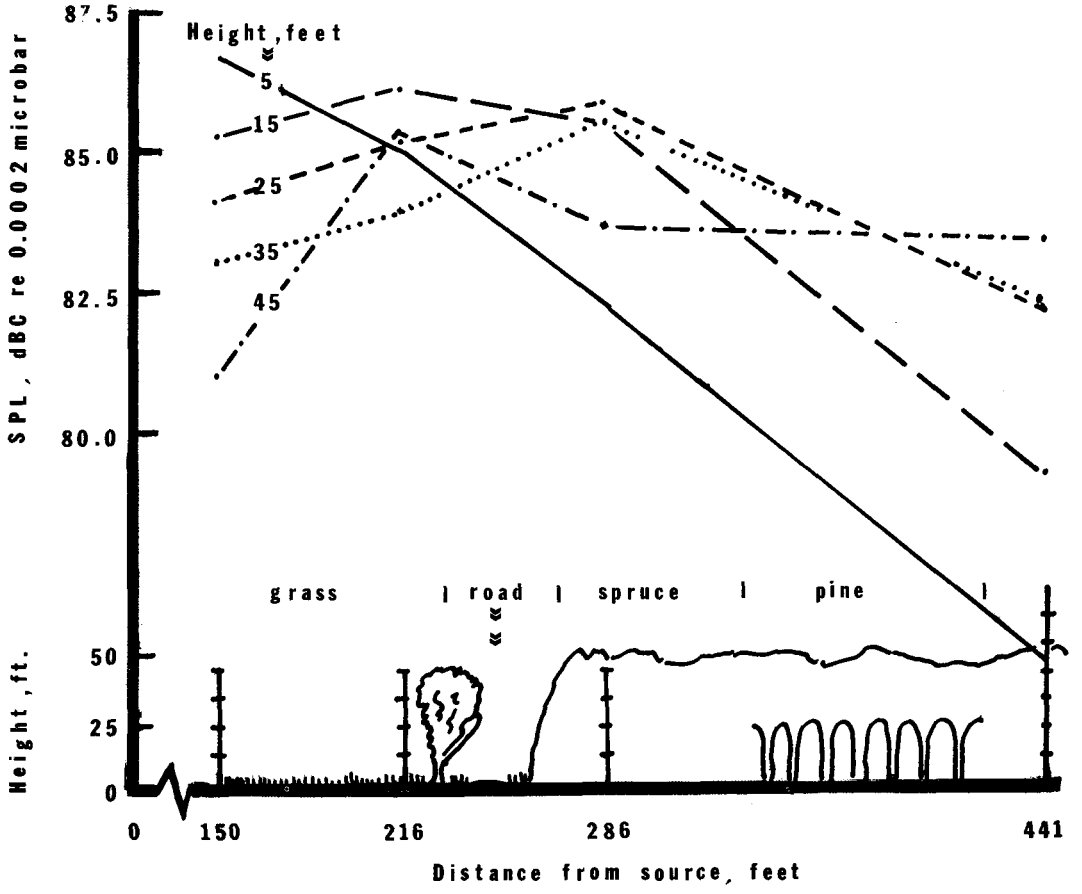
Wide-band pink noise (a spectrum of noise with equal energy per octave of frequency) was broadcast from a folded-horn speaker toward the edge of a coniferous plantation (fig. 1). Along the axis of propagation, five towers were erected. Two of these towers were located outside the forest, one was located on the edge of the forest, and two were located within the forest.

Microphones, which were attached to pulley systems on each tower, were used to measure the sound pressure level at the heights indicated (fig. 1). The pink noise (signal) received at each microphone was recorded on magnetic tape at the test control center. Both ambient noise—that is, the noise naturally present in the environment—and the signal were measured for each tower-height combination during 14 field-measurement periods. These periods were approximately 30 minutes in length. The field measurements were made under a wide range of meteorological conditions during the summer of 1974. The recorded data were subsequently analyzed on a real-time analyzer, using an averaging time of 128 seconds. In this fashion the acoustic field in a vertical plane containing the axis of propagation was determined.

For each measurement, meteorological data (temperature and temperature profile, wind and wind profile, relative humidity and solar radiation) were also recorded.

The forest consisted of a plantation made up of parallel bands of Norway spruce *(Picea abies)* and red pine *(Pinus resinosa)* 1-chain (66 feet) wide, ori-

Figure 1.—Excess attenuation at five heights for acoustic energy propagating over and through a forest edge. Included is a diagram of vegetative features along the path and the location of the towers from which measurements were made.



ented at an angle of 20 degrees to the axis of noise propagation. The spruce presented a very dense tangle of dead branches below the live crown, while the pine was naturally pruned to a height of approximately 30 feet. The edge of the plantation was defined by a road and a partial row of deciduous trees (fig. 1).

RESULTS AND DISCUSSION

Figure 1 shows the average corrected SPL at several heights as a function of distance into the plantation. Corrected SPL was calculated by adding to the recorded data the loss due to spherical spreading of the wave front (6 dB per doubling of distance). Thus, a horizontal line in figure 1 would indicate no excess attenuation.

SPL increased with height at the 150-foot tower and showed a mixed pattern at the plantation edge (216 feet). Measurements of the directivity of the horn used to generate the acoustic signal indicated that this increase in SPL with height was not due to directivity of the speaker. The conclusion, therefore, is that this pattern must be due to reflection of acoustic energy from the edge of the forest. The generally increasing SPL between the 150-foot and 216-foot towers supports this contention. At a

height of 5 feet there was little foliage at the edge, and there was a decrease in SPL at the 5-foot height between these points. The further increase in SPL between the 216-foot and 286-foot towers for heights of 25 and 35 feet may also be due to reflection of acoustic energy, but this is less clear than for the edge condition.

Within the forest there is a steady and rapid decrease in SPL at the 5-foot height. At higher elevations, however, the pattern is not as clear. The 45-foot height, which was just about at the top of the canopy, shows very little attenuation with distance; while the levels measured within the canopy do show some attenuation with distance. The 34-foot level, which was distinctly within the closed portion of the canopy, showed the strong attenuation between 286 and 441 feet from the source.

Two-way analysis of variance (height and distance) of the corrected SPL data showed, as might be expected, that total attenuation increases with the distance from the source. The analysis of variance also showed that there was significant variation of the attenuation pattern with height and that there was a significant interaction between height and distance. Grouping of the data in the analysis of variance procedure showed that there was no significant difference between the attenuation patterns at the 15-, 25-, 35- and 40-foot levels, but that there was a significant difference between the attenuation pattern at 5 feet and at the higher levels. That is, the pattern of attenuation near the ground is not the same as that which exists at 15 feet and above.

Based on their measurements of the acoustic absorptivity of bark, Reethof *et al. (1975)* have proposed that tree stems and branches are scatterers of acoustic energy and that absorption takes place mainly at the ground surface. Our results plainly support this argument and indicate further that there may be some attenuation in the thickest part of the canopy also.

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Some Physical and Psychological Aspects of Noise Attenuation by Vegetation

by DONALD E. AYLOR, *Department of Ecology and Climatology, The Connecticut Agricultural Experiment Station, New Haven, Conn. 06504.*

ABSTRACT.—The physical mechanisms governing sound attenuation by foliage, stems, and ground are reviewed. Reflection of sound energy is found to be the primary mechanism. In addition, new experimental results are discussed that help to quantify the psychological effect of a plant barrier on perceived noise level. Listeners judged the loudness of noise transmitted through hemlock trees and through a minimal fence barrier to differ by as much as 7 dB even though the sound level at the listener was the same.

CONSIDERABLE MEASUREMENTS OF NOISE muffling by plants have been made. To properly interpret these measurements, a firm understanding of the physical mechanisms of sound attenuation by plants is required. For example, many of the differences in sound attenuation by plants found by earlier workers *(Eyring 1946, Wiener and Keast 1959, Embleton 1963)* can now be reconciled by physics *(Aylor 1972a)*.

Besides physical effects, there can be psychological effects of plant barriers on the perception of noise. The visual shielding of a source by plants may have a beneficial effect for reducing the annoyance of noise *(Kurze 1974, Herrington 1974)*. So far, this potential psychological effect has not been quantified.

PHYSICAL EFFECTS

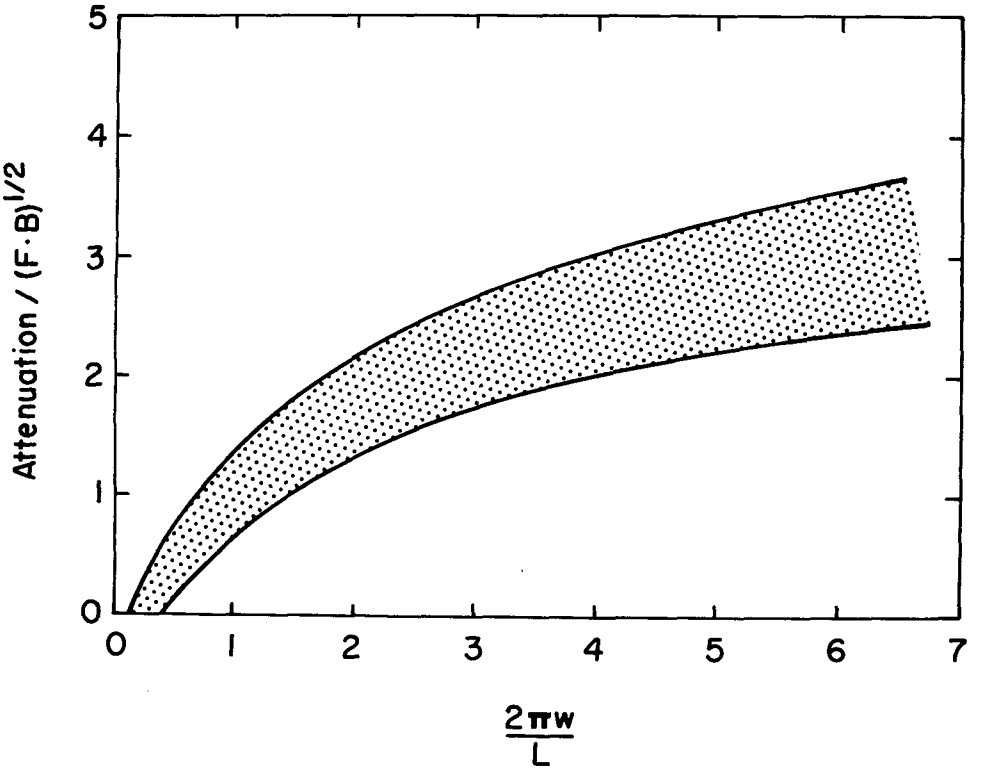
Plants can attenuate sound by reflecting energy, by absorbing energy in the viscous and thermal boundary layers near the plant surface, or by internal damping of sound-driven oscillations of branches or stems. Moreover, plants can modify the texture of the ground and thus alter sound attenuation by ground. Microclimate, which has profound effects on sound transmitted outdoors, will not be discussed here. For a review of meteorological effects on sound transmission see Ingard *(1953)*.

Scattering by Foliage

Sound is attenuated by foliage primarily by reflection or scattering. This conclusion is supported by the following observations: the attenuation of sound transmitted through foliage is much larger and increases more rapidly with sound frequency than predicted for absorptive mechanisms *(Aylor 1972a, Embleton 1963)*; attenuation does not increase in direct proportion to the amount of foliage, but rather less rapidly; attenuation of a given sound frequency increases with the width of the leaf *(Aylor 1972a and 1972b)*. Still further evidence indicating that foliage attenuates sound mainly by scattering, rather than by absorption, was deduced from measurements of sound reverberation between buildings covered with ivy *(Aylor et al. 1973)*.

Clearly, the energy transmitted through a canopy of leaves is scattered many times, and the mathematical solution of this multiple-scattering problem is evasive. Fortunately, however, the reduction of a direct beam of sound by foliage can be estimated in terms of the leaf area per unit volume of canopy, leaf width, breadth of the canopy, and wavelength of the sound (fig. 1). Because leaves diffuse concentrated sound effectively but absorb little, best results are obtained when a screen of vegetation is placed on a line of sight between a

Figure 1.—The shaded region gives an estimate of sound attenuation (dB) by foliage. F is leaf area per unit volume of canopy (m^{-1}), B is breadth of canopy (m), w is leaf width (m) and L is the wavelength of sound (m).



direct source of sound and a listener and closer to the source than the listener. Sound that is already diffuse is reduced relatively little.

Scattering by Trunks and Branches

Since trunks and stems are quite rigid, little energy is scattered when the wavelength of sound is large compared with their diameter. However, in the high frequency limit — when the wavelength is small compared to the stem diameter — the amount of scattered energy can be significant. For this limit, at the far edge of a dense forest, the attenuation A varies *(Aylor 1972a)* according to:

$$A \sim Z + \tfrac{1}{2} \log Z \qquad [1]$$

where $Z = 4\ N\ a\ y$ is the dimensionless scattering pathlength. N is the number of trees per unit land area, a is the average trunk radius, and y is the distance into the woods. This approximate expression is not valid for small Z.

The values of the parameter Na for most wooded sites range from 1×10^{-2} m^{-1} to 5×10^{-2} m^{-1}. The predicted attenuation due to stems for high sound frequencies at 100 m or so distance agrees fairly well with measurements *(Aylor 1972a)*. Finally, the principles of scattering show why visibility is a poor estimate of sound attenuation by trees. Because of the much shorter wavelength of light compared to that of sound, visibility is greatly reduced by small stems and needles. However, because of their small size, they do not scatter much sound.

Attenuation by Ground

When the source and receiver of sound are both near the ground, sound attenuation exhibits a maximum at a specific frequency *(Ingard 1953)*. This attenuation is due primarily to destructive interference between the direct and reflected sound at the receiver, and it depends on the source and receiver heights, source-to-receiver distance, and the acoustic impedance of the ground surface.

The phase of the reflected wave is retarded with respect to the direct wave by two effects. First, there is a delay due to the increased distance traveled by the reflected energy. In addition, for porous surfaces there is a phase lag due to interaction of sound with the surface. Because the ground is porous, it reflects sound only after a slight delay, while the air in the pores is being compressed. This delay, combined with the longer distance traveled, causes acoustic interference at the receiver. In general, the more porous the soil, the longer the delay in compressing air in its voids. The result is that the peak attenuation occurs at lower frequencies over more porous soils *(Aylor 1972a)* and is less dependent on source-receiver separation. Moreover, far from the source with both source and receiver near the ground, i.e. grazing incidence, ground attenuation is very nearly 6 dB per doubling of distance *(Ingard 1953, Aylor 1972a)*.

PSYCHOLOGICAL EFFECTS

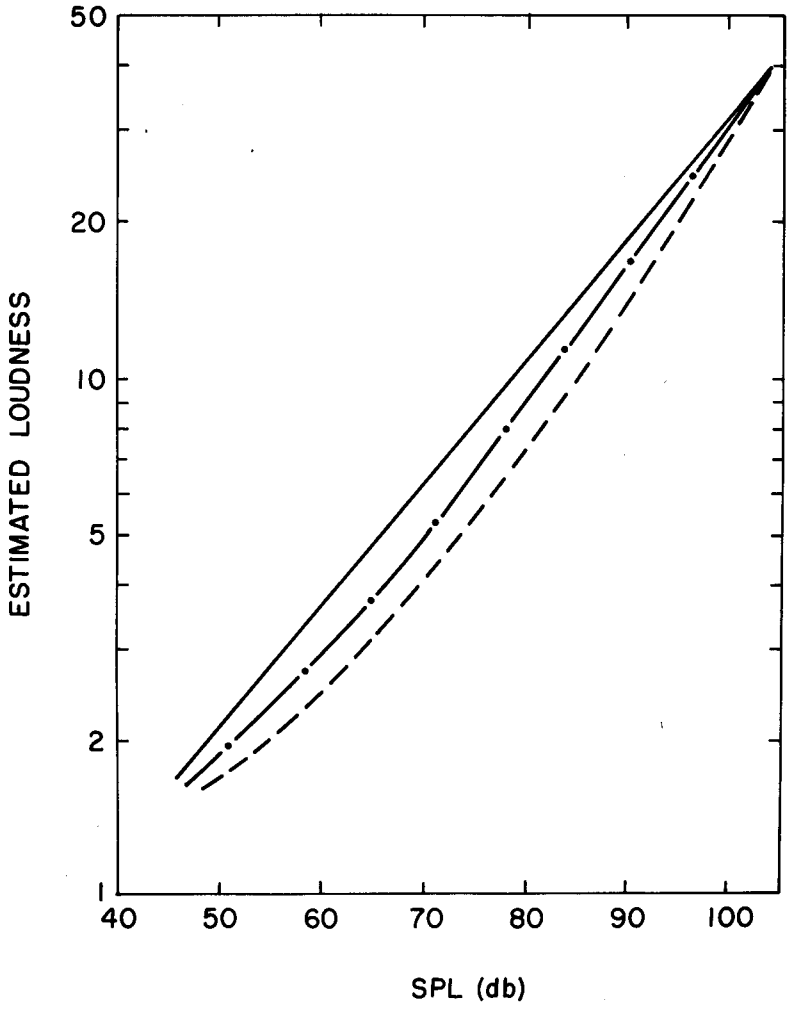
Although a narrow barrier of plants may give measurable attenuation of sound energy, some people believe that the visual shielding of the sound source may nevertheless have a positive or beneficial, psychological effect for reducing noise *(Kurze 1974 and Herrington 1974)*. To help define the interaction of sight and sound on perceived noise levels, Lawrence E. Marks of the John B. Pierce Foundation Laboratory in New Haven, Connecticut, and I asked human observors to scale numerically, by the method of magnitude estimation *(Marks 1974)*, the relative loudness of a narrow band of noise transmitted outdoors through barriers of different solidity.

Thirty subjects were asked to compare the relative loudness of a third-octave of noise at 1000 Hz transmitted to them through each of three barriers of contrasting physical characteristics or without an intervening barrier. The subjects were instructed to assign any number they wished to the first stimulus but to thereafter assign numbers in proportion to loudness. Sound levels, between 40 and 100 dB lasting 3 seconds, were presented at random from each of the four conditions. For each stimulus the subject faced the source of sound. In all, more than 1,400 separate loudness judgments were made when the barrier could be seen and the sound could be heard. As a control for our experiment, an additional 400 loudness judgments were made by 12 of these subjects while blindfolded.

The three barriers, constructed of acoustic tile, snow fence, or hemlock trees, with an identical sound source directly behind each one, as well as a source without any barrier, were arranged around a 15-foot radius circle. The barriers were about 3.7 m long and 1.5 m high. For the tile and hemlock barriers, sight of the source was completely obscured. The snow fence had a porosity of about 50 percent, so the source was only partially obscured, and, of course, for the no-barrier situation, the source was totally visible. Subjects were seated at the center in a swivel chair. The sound pressure level (SPL) was measured by a microphone centered about 15 cm above and facing towards the subject's head.

Geometric averages of the magnitude estimates of loudness and arithmetic averages of SPL (dB) were made for all subjects for each of the conditions. The blindfolded subjects, on the average, judged all conditions equally loud at the

Figure 2.—Averaged magnitude estimations of relative loudness vs. SPL (dB) for both tile and hemlock (solid line), slat fence (dashed line) and no barrier (dashed-dot line) situations.



same SPL. However, when the barriers could be seen, sizable differences in perceived loudness emerged (fig. 2). Although a given noise transmitted through hemlock (H) and tile (T) seemed equally loud, this same noise, surprisingly, seemed less loud when transmitted across an open unobstructed space (O) and even less loud when transmitted through the minimal snow-fence barrier (F). That is, to maintain a given loudness for the listener, more sound energy was required at the listener for the F and O than for the H and T conditions. At the mid-range of stimulus levels, this difference was as much as 3.5 dB for the open and 7 dB for the fence.

These results were evaluated statistically by fitting a separate psychophysical function *(Marks 1974)* for each subject and taking the difference of their magnitude estimates for each condition at 70 dB SPL. All differences except T - H were significantly different from zero.

Visual shielding of the sound source dramatically affects the perception of

sound transmitted through a barrier, but this effect is not related simply to shielding. As long as the source can be seen, reduced visibility is accompanied by a reduction in apparent loudness. However, when sight is completely obscured, this effect reverses, and the apparent loudness increases. This last result may (of course, many alternative explanations exist) hinge on people's expectation of a solid barrier's effectiveness. In that regard, it might be analogous to the well-known size-weight illusion, in which the weight feels heavier when it is compressed into a small volume *(Stevens and Rubin 1970)*. Based on experience, people generally expect that weight will increase with increasing volume, and thus the weight of massive object in a small container is often overestimated.

Perhaps this same kind of logic applies when a sound source is visually occluded by a barrier. Again, based on experience, people expect a solid barrier to reduce transmitted sound. Therefore, a given sound coming from behind a barrier seems surprisingly loud compared to one of the same level coming from a visible sound source and may, therefore, be overestimated. These results demonstrate a psychological effect of barriers on perceived loudness of as much as 7 dB. Unfortunately, the direction of this effect is not related simply to the visibility of the source. This certainly exemplifies the complex nature of the perception of environmental noise.

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Suburban Noise Control with Plant Materials and Solid Barriers

by DAVID I. COOK *and* DAVID F. Van HAVERBEKE, *respectively professor of engineering mechanics, University of Nebraska, Lincoln; and silviculturist, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

ABSTRACT.—Studies were conducted in suburban settings with specially designed noise screens consisting of combinations of plant materials and solid barriers. The amount of reduction in sound level due to the presence of the plant materials and barriers is reported. Observations and conclusions for the measured phenomenae are offered, as well as tentative recommendations for the use of plant materials and solid barriers as noise screens.

YOUR $50,000 HOME IN THE SUBURBS may be the object of an invasion more insidious than termites, and fully as damaging. The culprit is noise, especially traffic noise; and although it will not structurally damage your house, it will cause value depreciation and discomfort for you. The recent expansion of our national highway systems, and the upgrading of arterial streets within the city, have caused widespread traffic-noise problems at residential properties. Blame for the problem rests with governmental bodies at all levels, and with real-estate developers and the general public in its demand for rapid automobile access and movement. Rather than attempting to fix the responsibility, however, our objective is to help reduce the suburban traffic-noise problem, using combinations of plant materials and solid barriers.

THE ALTERNATIVES

Preliminary planning that includes noise considerations, adequate zoning, and setbacks offers the greatest assurance of a relatively noise-free suburban environment. Where the noise problem already exists, however, means are available for reducing noise to an acceptable level.

Ideally, noise is controlled by reducing the source level. Lowered speed limits, relocated truck routes, and improved engine muffling can be helpful. An alternative solution is to create some sort of barrier between the noise source and the property to be protected. In the Twin Cities, for instance, wooden walls up to 16 feet tall have been built along Interstate Highways 35 and 94. Although not esthetically pleasing, they have effectively reduced traffic noise, and the response from property owners has been generally favorable.

Land forms consisting of earthen dikes, also known as acoustical berms, have shown promise. Roadside developments, strategically placed to take advantage of natural hills and other topographic features, reflect good planning to reduce noise from passing traffic.

Trees, shrubs, grass, and other plant materials can significantly reduce certain noises; and where conditions favor their use, no other means may be required.

HOW MUCH REDUCTION IS NEEDED

The amount of reduction in noise (attenuation) needed is determined by the level at the source and by requirements at the receiver. Source noise emitted by a large truck often exceeds 100 decibels (dBA) within a few feet of the vehicle. Requirements at the receiver vary considerably, depending on per-

sonal sensitivity, but most observers think that noise levels exceeding 70 dBA are objectionable for outdoor daytime activities, especially if conversation is to be maintained. (A reduction of 10 dBA means noise is cut about in half.) We favor levels in the 60- to 65-dBA range for daylight hours, and 50 to 55 dBA for evening hours, when background sounds are quieter. Our experience indicates that the majority of persons living adjacent to a 35-mile-per-hour arterial street do not object to noise levels in the 60- to 65-dBA range in their backyards.

To further illustrate the amount of reduction needed, consider a hypothetical situation in which the noise level of a large truck is 90 dBA at a point 10 meters from the center of the traffic lane. We would like to reduce the noise level to an acceptable 65 dBA at 30 meters from the same point. Some reduction occurs naturally with distance. Assuming a point source and spherical divergence, we would find the level at 30 meters to be about 80 dBA. The remaining 15-dBA reduction would have to come from some form of barrier interposed between source and receiver. However, neither a belt of tall dense trees, nor a solid wall of reasonable height, nor any combination of the two, will provide sufficient attenuation. Thus this situation represents a condition that can be remedied only by source-level reduction. It would therefore seem that heavy truck traffic, at its present high noise-emission level, should be excluded from suburban residential areas.

Consider a second illustration in which the noise level of an automobile is 75 dBA at a point 10 meters from the center of the traffic lane. The level at 30 meters is then only 65 dBA, which is acceptable to many persons for daytime outofdoor environments, although unsatisfactory for evening hours. We need only to reduce the level by as much as 5 to 10 dBA to provide a satisfactory acoustical environment in this case.

HOW MUCH REDUCTION IS POSSIBLE

With the means considered — plant materials and solid barriers — the amount of reduction possible depends largely on the height of the structure and the density and extent of the plant materials. Plant materials, by themselves, are capable of reducing noise levels as much as 8 dBA, and occasionally more. A tall masonry wall or earthen dike is capable of reducing noise levels by 15 dBA, when properly placed. However, practical considerations such as local ordinances, expense, and appearance rarely permit the construction of a solid barrier of sufficient height (12 to 20 feet) in residential areas.

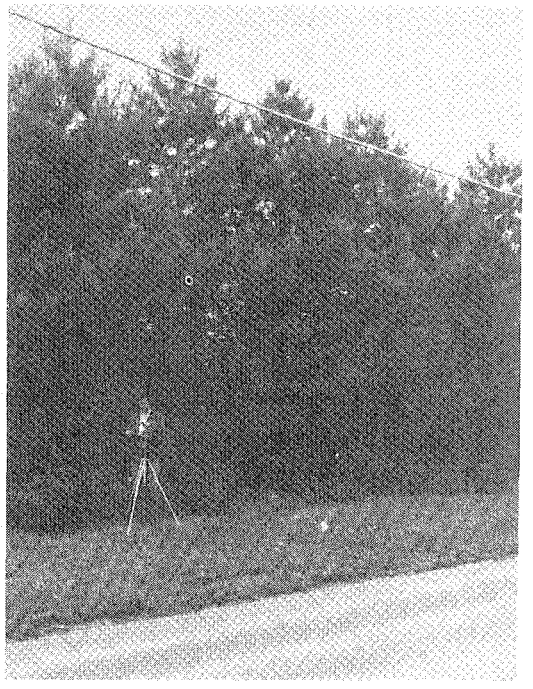
Our earlier studies in rural areas, where we used combinations of 12-foot-high solid earthen dikes and large dense trees, showed that reductions of 12 to 18 dBA are possible. Results of current experiments in suburban areas are not yet complete, but it appears that combinations of lower solid barriers and moderate-size plantings are also effective.

SITE SELECTION AND PROCEDURE

Ten residential properties in an upper-middle-class neighborhood were selected for study. Backyards of the properties faced a heavily traveled arterial street with a 35-mile-per-hour speed limit. Screen plantings and ground-surface configurations varied considerably from site to site. Three sites that illustrate the most significant features, for noise-control purposes, are described here (figs. 1, 2, and 3).

A sound-level meter was used to measure the noise of a vehicle as it passed by a test site, and a second meter was used to measure noise from the same vehicle as it passed by an open (control) area immediately thereafter. The difference in the two readings (attenuation) represented the amount of reduction that could be attributed to trees and shrubs, solid barriers, and ground-profile effect.

Figure 1.—Site 105 as viewed from the street. Low, dense, cotoneaster shrubs were backed by tall ponderosa pines.



The procedure was repeated at distances of 5, 10, 15, and 20 meters from the curb.

A special site, with relatively young trees on University of Nebraska property, was also selected to provide additional flexibility and control for the experiments. Here a power lawnmower was used as a noise source, and both microphone and source positions were varied. A concrete block wall (figs. 4 and 5), the height of which could be changed by adding courses, was also used in combination with the trees. One segment of the wall was placed in an open area, and an identical segment was placed within the tree belt.

Sound levels were measured by using three different barrier treatments and a control. In one case trees alone were located between the noise source and receiver; in a second case the wall alone was used; in the third both trees and wall were used. Source and receiver distances from the wall were varied from 5 to 20 meters. Readings were taken at various positions to determine the effects of wall, trees, and distance in reducing noise levels.

Figure 2.—Site 108 as viewed from the street: medium-height plantings, a woven board fence, and a downward-sloping ground profile from street to residence.

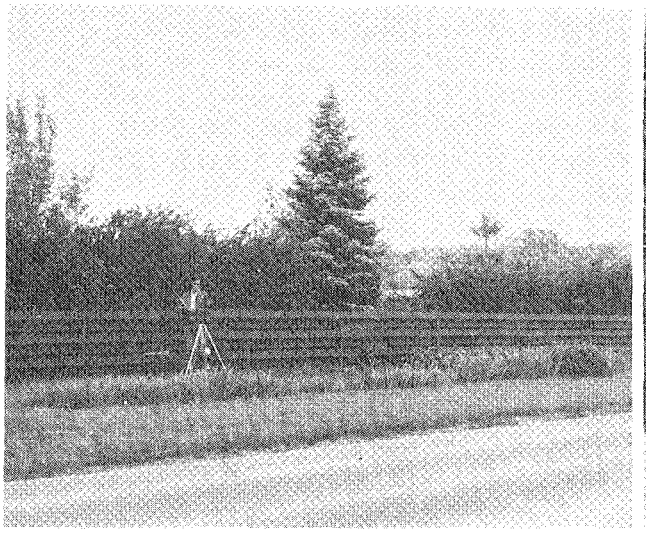


Figure 3.—Site 107 as viewed from the street: tall evergreens hide a 3- to 6-foot brick wall, and an upward-sloping ground profile from street to residence.

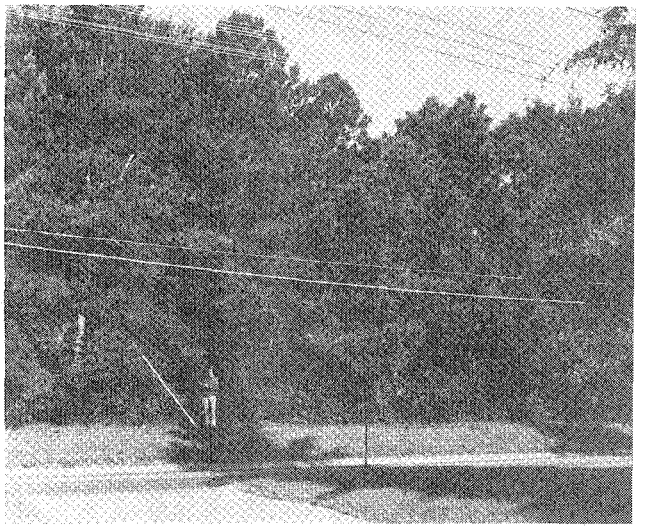
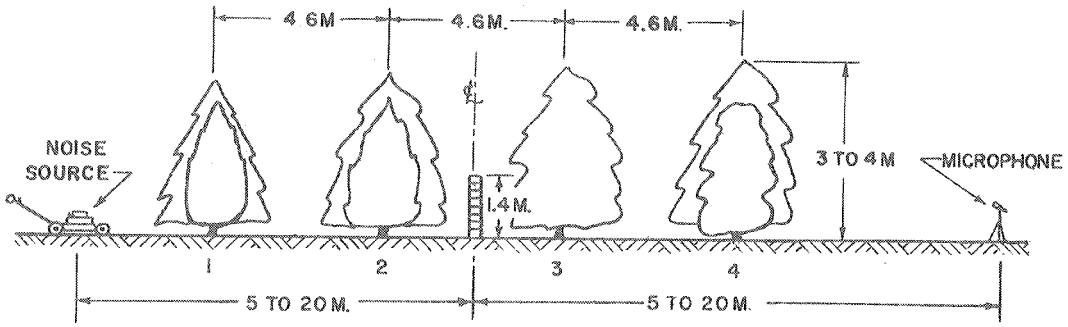


Figure 4.—Site 111: Schematic diagram of wall within belts of trees.

SITE 5

PLATTSMOUTH BELT AND WALL



ROW NO	NAME OF TREE
1	AUSTRIAN PINE ALTERNATED WITH ROCKY MT. JUNIPER
2	PONDEROSA PINE ALTERNATED WITH EASTERN REDCEDAR
3	SCOTCH PINE
4	AUSTRIAN PINE ALTERNATED WITH ORIENTAL ARBORVITAE

(TREE SPACING IN ALL ROWS – 2 M.)

Figure 5.—Site 111: top, the sound-barrier wall; bottom, the belts of trees.

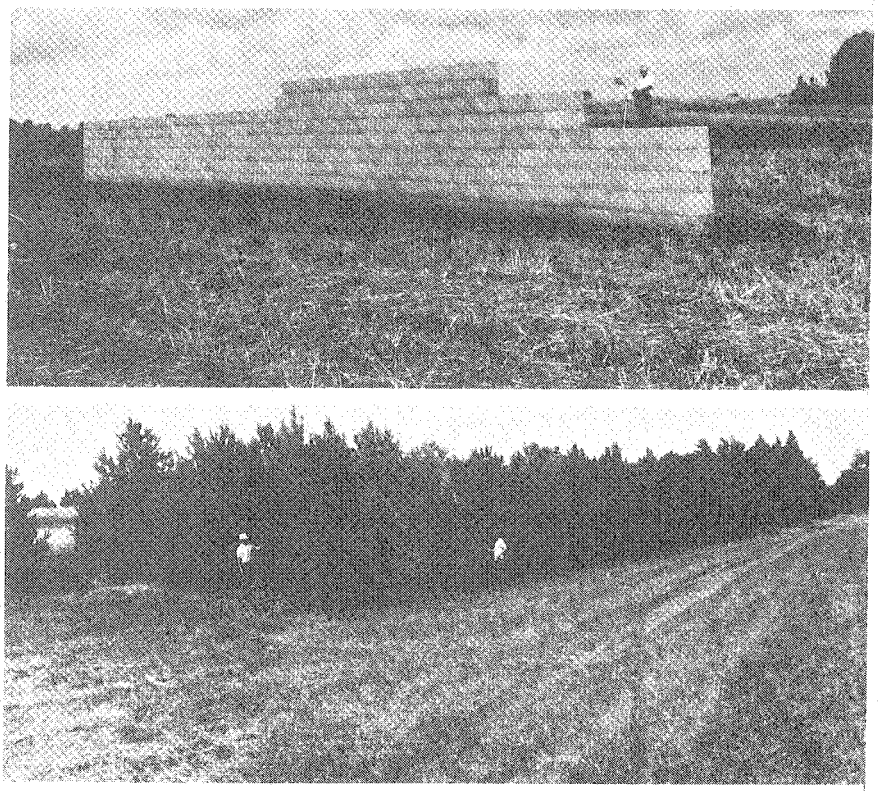


Figure 6.—Site 105: profile of site, noise level, and attenuation.

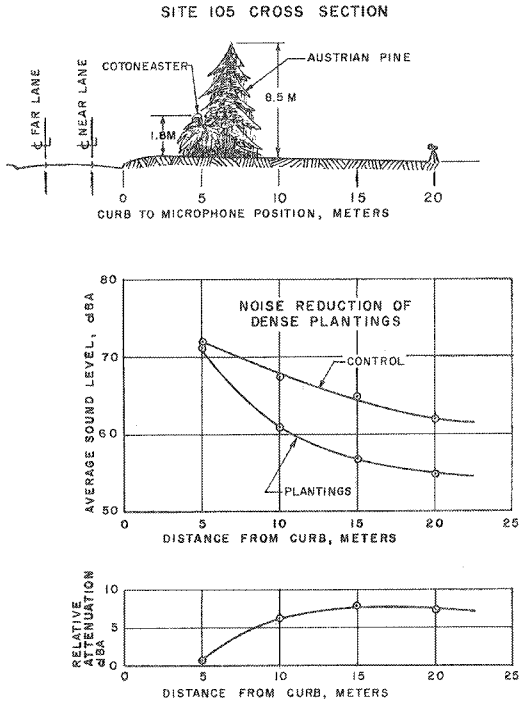


Figure 8.—Site 107: profile of site, noise level, and attenuation.

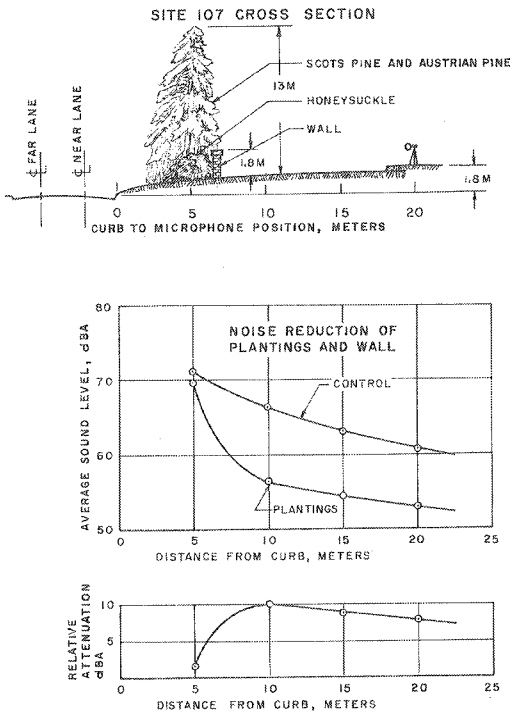
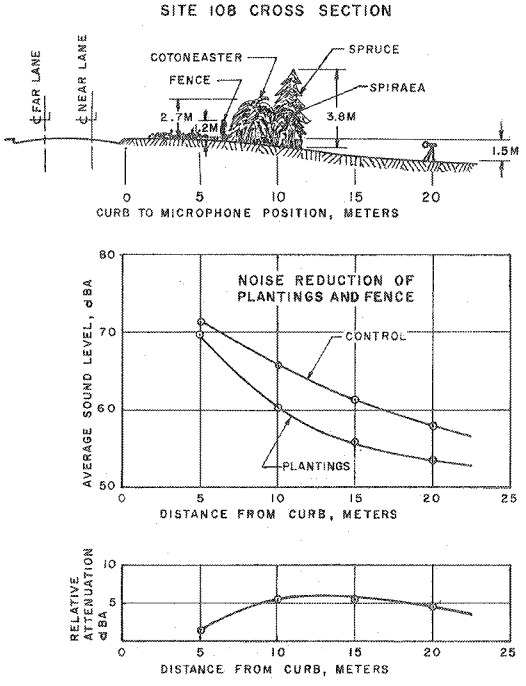


Figure 7.—Site 108: profile of site, noise level, and attenuation.



RESULTS OF EXPERIMENTS

Suburban Sites

Noise reduction characteristics of the three sites are shown graphically in figures 6, 7, and 8. Curves are positioned directly below the schematic cross-section drawings so the points denoting sound level and attenuation line up with the corresponding microphone positions. All readings are in dBA units.

Tree-Farm Site

Variation of sound level with distance and attenuation for the different surface treatments is shown in figure 9. The full height (1.6 meter) wall and the 10-meter wall-to-microphone distance were used in this instance.

The effect of different wall placements —between source and receiver—on the

Figure 9.—Sound level and attenuation with different surfaces.

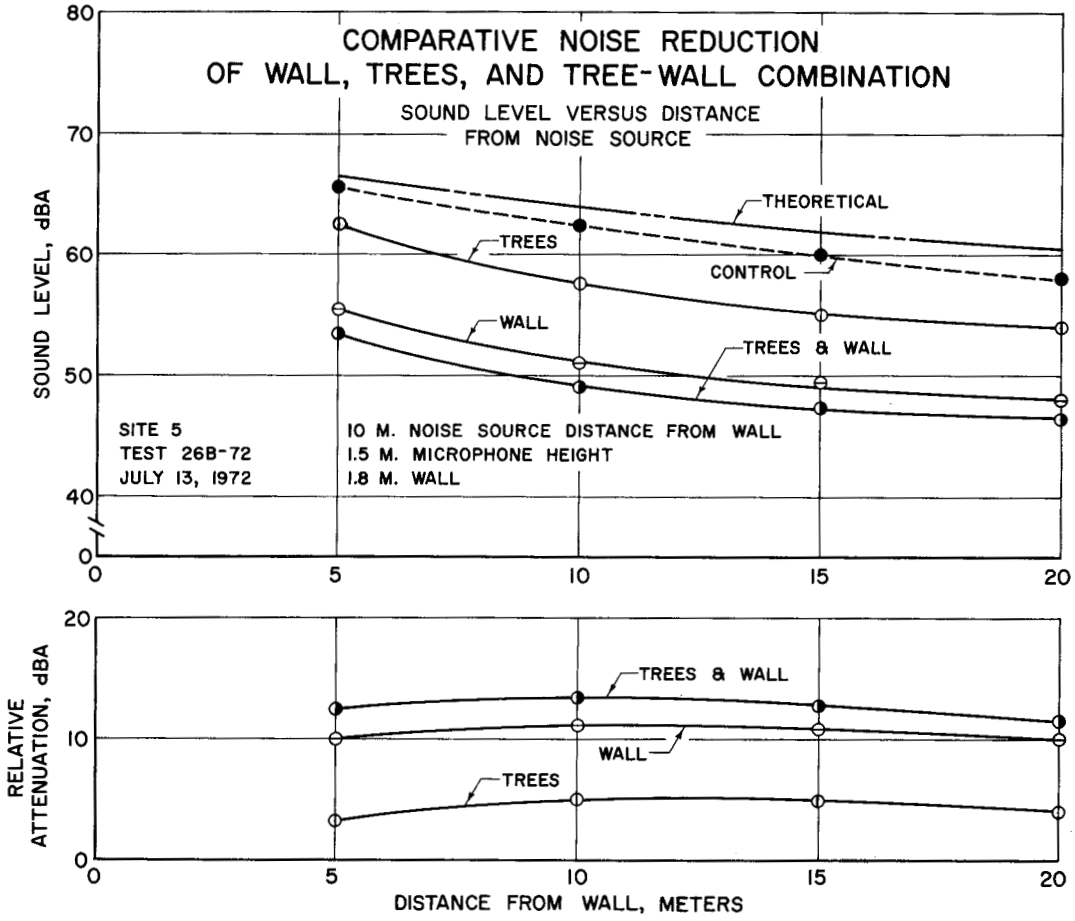


Figure 10.—Effect of wall placement.

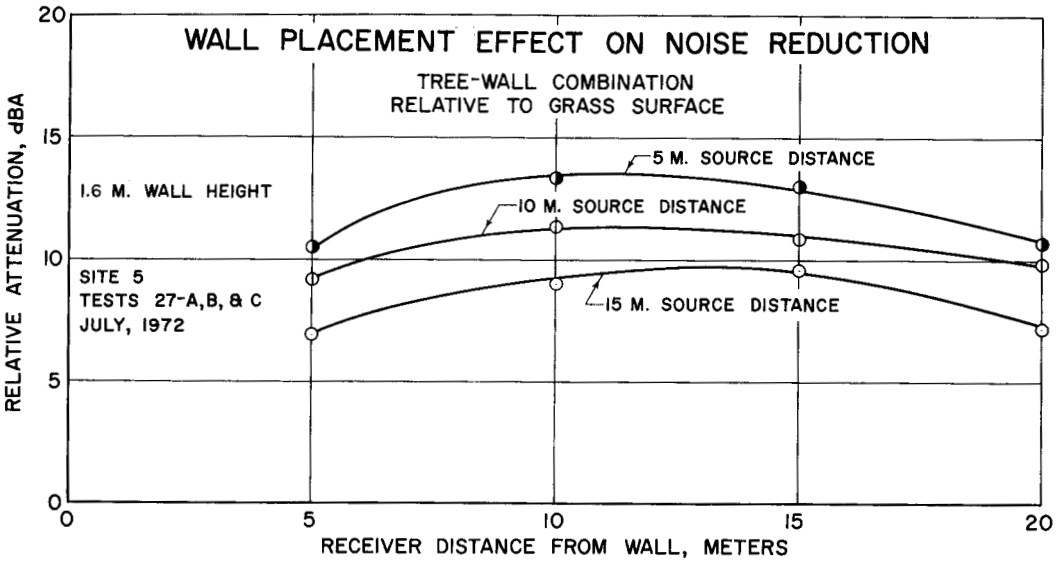
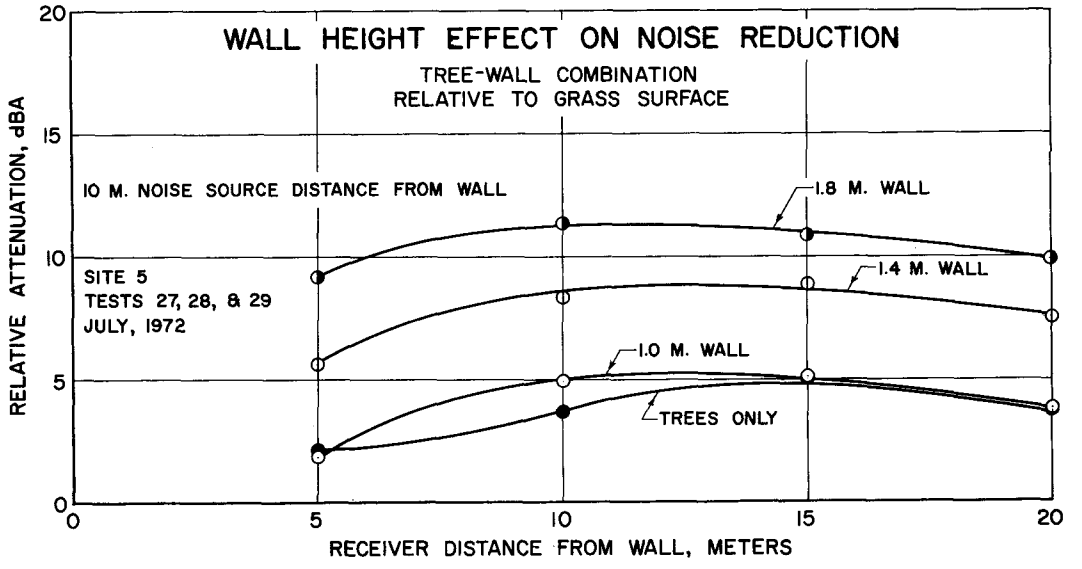


Figure 11.—Effect of wall height.



attenuation obtainable is shown in figure 10.

The effect of walls of different height combined with trees is illustrated in figure 11. A trees-only curve has been included for comparison.

OBSERVATIONS AND CONCLUSIONS

Results of the current series of suburban experiments are not fully analyzed at this time, and further experiments under controlled conditions are scheduled for next summer. Although our conclusions must be somewhat tentative, the general pattern of results is consistent and reliable.

At some of the sites, it appears that existing natural barriers, combined with additional plantings and some form of a low solid barrier, are adequate for the control of traffic noise from 35-mile-per-hour automobiles (figs. 6, 7, and 8). For similar suburban sites, continuous plantings of dense shrubs backed up by taller trees, as in the case of site 5 (figs. 1 and 6) are capable of providing sufficient protection from automobile and light truck traffic noise.

Where individuals are more sensitive to noise, or where the residence is rather close to the traffic lane, additional protection in the form of a higher solid barrier, such as an earthen dike, solid masonry wall, or tight wooden fence may be necessary.

It also appears that there is no practical means for reducing noise from large trucks to a level acceptable in suburban areas. The source itself must be brought under control.

RECOMMENDATIONS

1. To reduce noise from suburban automobiles and light trucks to an acceptable level where the residence is at least 25 meters from the centerline of the roadway, plant one or two continuous rows of dense shrubs as close to the curb as possible, and one or two continuous rows of dense trees behind the shrubs. One or both plantings should be of evergreens for year-round protection.
2. Where immediate relief from traffic noise is desired, erect an earthen dike, masonry wall, or solid wooden fence. The height should be sufficient to screen the noise source from view at the location to be protected. Landscaping should be included to provide

additional protection, when the trees become larger, and to decrease the reflection from the hard wall surface back across the street.

3. Where the residence is less than about 20 meters from the centerline of the roadway, both trees and a solid barrier are necessary.

Role of Land Use Planning in Noise Control

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This study was supported primarily by the Massachusetts Agricultural Experiment Station, University of Massachusetts (paper No. 1061), with additional support from the U.S. Department of Interior Office of Water Resources Research and the USDA Forest Service, Northeastern Forest Experiment Station, Pinchot Institute for Environmental Forestry Research.

ABSTRACT.—A method for controlling outdoor noise through land use planning is presented. The method utilizes a computer model that broadly assesses the likely noise environments of a community on the basis of generalized land use and highway noise production and transmission conditions. The method is designed to enable town planners and other community decision-makers to identify those general areas that are potentially unsuitable for noise-sensitive types of development such as housing. The method also predicts probably changes in noise environments and in the suitability of those environments due to general changes in land use (development). The method does not require site-specific measurements.

AS THE INTEREST of this conference in the acoustic environment indicates, noise pollution is one of the hazardous and disagreeable byproducts of human activity that warrants control. Historically, noise has been an undesirable feature of city life. Since World War II, however, it has become an undesirable feature of communities in general. The population explosion of recent decades and the subsequent process of decentralized development have brought increasingly large numbers of suburban as well as urban residents into objectionable proximity to proliferating sources of noise.

Insofar as the actual noise levels of offending sources in the environment are not likely to be reduced for some time, the abatement of noise pollution today depends largely on our ability to control noise in transmission. Controlling sound in transmission involves manipulating the effective proximity of a noise source and the noise-sensitive receiver. In the outdoor environment, this manipulation constitutes the role of land use planning in noise-pollution control.

Noise planning controls may operate at either of two scales. At a larger planning scale are general land use allocation noise controls. These are primarily allocations of various types of development within a larger landscape context (such as a town) to appropriate noise-environment zones. In other words, noise-sensitive land uses are allocated to quieter zones and noisier land uses are allocated to noisier zones. Noise control is for the most part a matter of isolating or aggregating land uses to prevent the undesirable exposure of noise-sensitive areas. At this scale, specific types of noise buffers between uses are not considered.

At a smaller planning scale are what might be called land use management noise controls. These include the provision or enhancement of various types of noise buffers between acoustically incompatible land uses. In other

words, barriers, forests, fields, distances, and other buffers are maintained or managed between noisy land uses (factories, highways, shopping centers) and noise-sensitive land uses (neighborhoods, schools, hospitals). Generally at this scale, a particular noise problem is either controlled (for example, by constructing a berm between a housing development and a highway) or prevented (for example, by siting a school at a suitable distance from a factory).

To date, these opportunities for noise control through land use planning have not been presented in terms particularly useful to planners and other decision-makers. With the exception of a highway-noise-simulation model developed by the firm of Bolt Beranek and Newman *(Galloway et al. 1969)*, previous outdoor noise assessment techniques, notably "community noise reaction models" *(Great Britain Committee 1963, EPA 1972)*, have relied entirely on site-specific measurements. Such measurements are both time-consuming and costly and therefore highly impractical for many planning purposes. In addition, site measurements are really useful only in defining existing noise problems such as the extent to which noise from an airport affects the noise character of the surrounding landscape. Moreover, measurements require that each noise problem be evaluated separately on the basis of measurements pertaining only to that particular problem. In general, present noise models cannot be used practically to assess multiple noise problems. Nor can they be used to predict the probable effects of proposed noise intrusions (airports, industries, and shopping centers) on surrounding environments.

Planning, however, relies upon tools that are both practical and predictive; that is, assessment techniques and planning guidelines that can be used with relative ease to evaluate in a general way a wide variety of existing or potential landscape situations. The almost total lack of such tools for noise-related planning purposes has led to the research reported here. A computerized technique or methodology for controlling outdoor noise through land-use planning is discussed.

This technique is intended to provide a practical basis for larger scale noise-related land use planning. Specifically, our methodology is designed to enable planners and other decision-makers to broadly identify those areas of the landscape within a community context that are potentially unsuitable for noise-sensitive types of development (for example, housing). It is further designed to predict probable changes in noise environments and in the suitability of those environments due to general changes in uses of the landscape. The notable feature of the methodology is that it does not require site-specific measurements.

We have also developed a nonmeasurement technique to aid smaller scale noise-related land use-planning and management decisions *(Fabos and Caswell, 1977)*. However, this technique, which is designed to enable users to estimate and avoid (through buffering) potential noise conflicts between adjacent but different uses of the landscape, is not discussed here.

This noise-pollution planning technique was developed as part of a larger interdisciplinary research effort (ongoing at the University of Massachusetts) known as the Metropolitan Landscape Planning Model Project *(Fabos 1973)*. For a discussion of the nature and operation of the Metropolitan Landscape Planning Model, which deals with a variety of resource, hazard, and use-suitability aspects of the landscape, see the paper by Fabos and Ferris included in these proceedings.

THE NOISE ENVIRONMENT ASSESSMENT METHODOLOGY

Noise is a dynamic phenomenon that, once generated by a source, travels over

a number of transmission paths to receivers located at various distances from the original point or area of noise output. The noise level at a given receiver therefore depends upon the original strength of the noise at the source and upon the degree of loss in this strength that is caused by the physical characteristics (trees, hills, pavement) of the transmission path along which the noise has traveled.

The present noise methodology is based on this acoustic principle. For any given community, procedures were developed for determining: (1) noise source areas and the likely strengths of these sources, (2) transmission loss areas and the likely degree of noise reduction provided by these areas, and (3) the probable noise environments that result from the transmission of noise from noise source areas through transmission-loss areas to other parts of the community.

The basis for these three procedures is described below. An exemplary application of the methodology to the Town of Burlington (located in the northwestern section of the Boston metropolitan region) for data relating to 1971 is used to illustrate each procedure.

Procedure for determining noise source areas

The procedure for determining noise source areas is based on two general types of noise sources that may appear in the landscape: (1) land uses and (2) highways.

Noise source areas were determined first by assigning a characteristic noise level to each land use and highway type, and second by aggregating those land uses and highways having similar noise levels into land use and highway noise groups (tables 1 and 2). The mapping of these groups for any town would

Table 1.—Assigned land use noise levels and resultant land use noise groups for land uses in the Town of Burlington in 1971

[A 1971 land use map aggregated according to these land use groups would yield a map showing the various land use noise source areas comprising the town for that year.]

Land uses in land use noise group	Assigned land use noise level
	dBA
Open space (wetland, forest, openland, abandoned land)	35
Farmland Orchard Nursery Cemetery Estate	40
Low-density housing	45
Medium-density housing; low-intensive recreation (golf course, driving range, drive-in)	50
Townhouse Garden apartment Public institution	55
Lighter industry	60
Shopping center Medium intensive recreation (playground, athletic field)	65
Strip commercial Intensive recreation (amusement park)	70
Core commercial Heavier industry	75
Mining (sand and gravel and traprock)	80

Table 2.—Estimated highway noise levels and resultant highway noise groups for secondary and primary roadways in the Town of Burlington in 1971

[Noise levels are based on near-peak to peak-hour conditions of road use. A 1971 road map (USGS toposheet), aggregated according to these highway groups, would yield a map showing the various highway noise sources comprising the town for that year. It should be noted that at the time of this mapping, the topography of the town would be used to make noise adjustments for steep roadway gradients.]

Highway (HW) characteristics	Noise level (listener location = 12.5')
	dBA
HW_1: 25 mph, 5-10 vehicles per mile; No % heavy trucks or buses; even flow; good road surface; shallow gradient	60
HW_2: 30 mph, 10-15 vpm; 2.5% heavy trucks or buses; even flow; good road surface; shallow gradient	65
HW_3: 35 mph, 20 vpm; 5% heavy trucks or buses; even flow; good road surface; shallow gradient	70
HW_4: 35 mph, 30 vpm; 5% heavy trucks or buses; even flow; good road surface; shallow gradient	72
HW_5: 35 mph, 30 vpm; 5% heavy trucks or buses; uneven flow; good road surface; shallow gradient	76
HW_6: 40 mph, 35 vpm; 10% heavy trucks or buses; even flow; good road surface; shallow gradient	
HW_7: 35 mph, 40 vpm; 10% heavy trucks or buses; uneven flow; good road surface; shallow gradient	79
HW_8: 50-55 mph, 60 vpm; 10% heavy trucks or buses; even flow; good road surface; shallow gradient	
HW_9: 60-65 mph, 90 vpm; 10% heavy trucks or buses, even flow; good road surface; shallow gradient	85

then yield the various noise source areas occurring within that town.

Land use noise levels were assigned on the basis of results of a recent outdoor noise-environment measurement survey undertaken by the State of California *(EPA 1972)*. Although the noise produced by a noise environment varies greatly over a 24-hour period, this survey statistically reduced the time-varying noise output of each measured environment to a single composite noise level in dB(A). (DB(A)'s are frequency-weighted decibels measured on an A-network sound-level meter.) In cases where the surveyed environment was a single-use environment comparable to a land use type, the measured statistical noise level was assumed to be a valid expression of the noise generally associated with that land use type. The noise levels of land use types not specifically sampled by the measurement survey were estimated on the basis of the similarity of their noise-producing characteristics to one or another of the measured environments.

Highway noise levels were assigned according to the highway noise simulation model developed by Bolt, Beranek, and Newman *(Galloway et al. 1969)*. This model estimates the noise level in dB(A) of any highway on the basis of the typical noise contributions of its road and traffic characteristics. These include vehicular density (in vehicles

Table 3.—Transmission loss groups and figures based on dominant land use characteristics for land uses in Burlington in 1971

[A 1971 land use map aggregated according to these groups would yield a map showing the transmission loss areas comprising the town for that year. Transmission loss figures are given in decibels per thousand feet (dB/1000') or decibels per doubling of distance (dB/dd), depending upon which rate of noise reduction is more appropriate for the predominant landscape characteristic.]

Dominant physical characteristic	Land uses in transmission loss group	Transmission loss figure	
		dB/1000'	*dB/dd*
Wet land	Wet land	—	1.0
Grass/low vegetation	Farmland, open land, golf course, playground, cemetery, athletic field	—	3.0
Trees (less than 30% crown closure)	Orchard, nursery, abandoned land, estate	—	4.0
Trees (30-80% crown closure)	Forest	—	4.5
Trees (greater than 80% crown closure)	Very dense forest	—	5.0
Hard ground/pavement	Amusement park, drive-in	1.0	—
1-2 story structures (scattered)	Low-density housing	3.0	—
1-2 story structures (less scattered)	Medium-density housing	5.0	—
1-2 story structures (very large)	Shopping center, strip commercial, heavy industry	6.0	—
2+ story structures	Townhouse, garden apartment, light industry, public institution, core commercial	10.0	—
Land form	Sand and gravel, traprock mining	8.0	—
Water	Open water	0.0	—

per mile), vehicular speed (in miles per hour), traffic composition, traffic flow, road surface, road gradient, and listener location.

Procedure for determining transmission loss areas

The procedure for determining transmission loss areas is similar to that used for determining land use noise source areas. Transmission loss areas were determined first by grouping land use types according to the similarity of their dominant physical characteristics (pavement, grass, trees, one-story buildings, etc.), and second by assigning to each group a figure of transmission loss that reflected in a very general way the rate of noise reduction provided by that group's dominant physical characteristic (table 3). The mapping of these groups for any town would then yield the various transmission loss areas occurring within that town.

Transmission loss figures were extrapolated wherever possible from the results of previous studies concerned with the transmission of noise in the outdoor environment *(Simonson 1955, Embleton 1963, Winterbottom 1965, Sexton 1969, Robinette 1972, Aylor 1971 and 1972)*. They are, however, only very general estimates of average landscape transmission loss and do not account for noise reductions due to air, temperature, wind, or possible differences in terrain.

Procedure for calculating noise environments

A computer model was developed to compute the various noise environments that would result when noise from

source areas traveled through transmission loss areas to other parts of the town. The model assumes that each noise source area mapped for a town can be represented as an aggregate of smaller individual noise sources or sourcelets distributed either within that area (in the case of land use noise sources) or along the length of that area (in the case of highway noise sources).

To establish a basic acoustical relationship between the noise level corresponding (assigned) to a noise source area and the noise strengths of the sourcelets necessary to produce that noise level, the model further assumes that the noise strengths of sourcelets comprising a land use noise source area are such that, if the entire mapped region were composed of the same sourcelet strengths and the same rate of transmission loss, the noise level corresponding to that land use source area would result. Analogously, the model assumes that the noise strengths of sourcelets along a highway noise source are such that, if the highway were straight, the noise level corresponding to that highway source would result.

Input to the computer model includes sets of digitized data corresponding to numerous points (sourcelets) on the noise source and transmission loss maps. These digitized points serve to locate on an x-y coordinate system the sourcelets distributed within each land use noise source area and transmission loss area and along each highway noise source area mapped for a town. The sets of digitized data corresponding to each map are then successively manipulated by four computer programs run in a prescribed sequence.

The final printout is a spatial display of originally digitized points. At each point, the "new" noise level resulting from the transmission of sourcelet noise through the landscape is given in symbolic form. The computation of these new noise levels includes the effects of spatial attenuation — the natural reduction in noise due to spherical spreading as noise travels away from a source.

Each symbol on the final printout represents a 10-dB(A) range of noise levels. By manually tracing a line along the interface of different printed symbols and by converting these symbols to the noise-level ranges they represent, a noise map is produced. This map illustrates what are in effect the various general noise environments of the region represented by the original noise source and transmission loss map (fig. 1).

Utility of the noise map

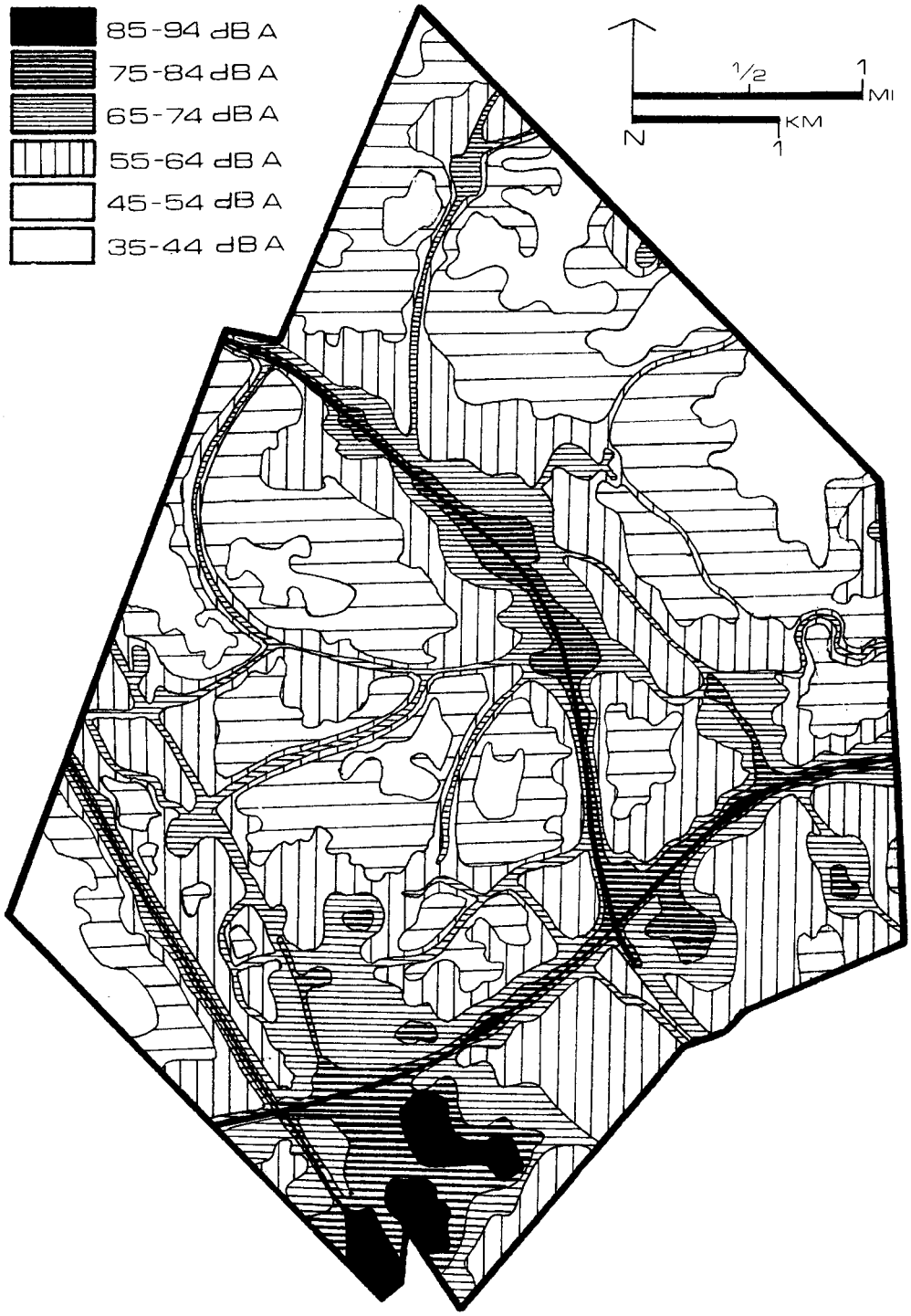
With the noise map, a planner or other decision-maker is for the first time provided with the information necessary to carry out planning policies that reflect the potential noise suitability of different parts of a town for different types of development.

For example, a planner might decide that it is desirable to restrict all future noise-producing landscape uses such as airports, shopping centers, and certain industries to already noisy areas. The noise map of the town shows where these existing noisier environments are. Alternatively, the planner might decide to set aside quite areas of the town for the location of proposed noise-sensitive uses such as low-density housing, hospitals, schools, and libraries. Again, the noise map of the town shows where these quieter environments are.

In his approach to these noise control planning decisions, the planner may be as specific or as general as the noise map allows. On one hand, he may establish detailed development policies for each of the different noise environments appearing on a noise map. On the other hand, he may choose to group several noise environments into a few major noise categories, which generally summarize his noise planning objectives for the town.

A review of pertinent literature indicates that there are two views or concepts of environmental noise pollution

Figure 1.—The 1971 noise map produced by computer for the Town of Burlington, Massachusetts. The map is based on the noise interaction among land use and highway noise source areas and transmission loss areas occurring in the town in 1971.



that might be used to provide a basis for a more specific approach to noise control planning and decision-making.

The first view or planning concept is based on noise-complaint history and urban noise-annoyance surveys *(Great Britain Committee 1963, EPA 1972)*. This view suggests that all acoustically different uses of the landscape are to varying degrees incompatible and so should not occur adjacent to one another without some buffering. In other words, the various noise environments on a noise map would be to some extent degraded if land uses or highways having noise levels (tables 1 and 2) above 10-decibel noise level ranges were allocated to those environments. The greater the difference between the noise level of the proposd use and the noise-level range typical of the existing environment, the greater the loss in noise quality to the affected part of that environment, assuming no noise buffering landscape devices (trees, hills, berms, etc.) are already present or are intended to be used.

The second view or planning concept is based on people's reactions to aircraft noise *(Kryter 1968)*. This view suggests that intrusive outdoor noise constitutes no perceivable impact when below a basic annoyance threshold of about 55 dB(A). In other words, the introduction of a use having a typical noise level of 55 dB(A) or less would not be expected to negatively affect the noise quality of any noise environment appearing on a noise map, even if the environment in question were substantially quieter than the proposed use.

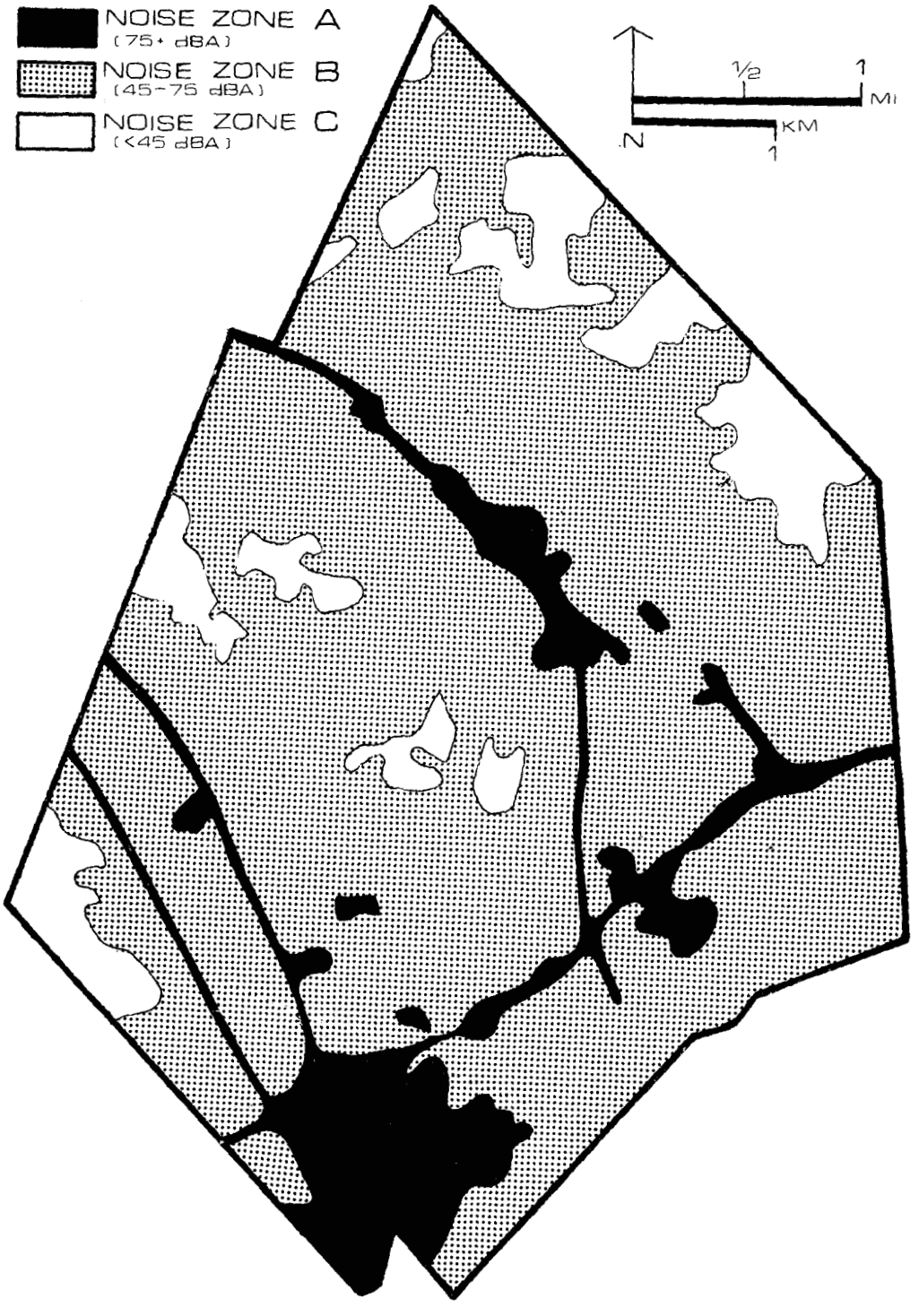
According to the first of these noise control planning concepts, a town planner may reasonably establish a development policy whereby only uses that are as quiet as or quieter than an existing noise-map environment may be introduced into that environment unless special measures are taken. Alternatively, according to the second planning concept, the planner may reasonably establish a similar but less stringent (and perhaps less ideal) development policy affecting only those proposed uses whose typical noise levels exceed 55 dB(A). Either way, the point is that the planner is enabled by spatial information in the form of a noise map to formulate specific noise pollution prevention policies and plans for all sectors of his community.

A more general approach to noise control planning and decision-making would be to use the noise map in a somewhat different way. A practical example of this type of approach might be as follows.

On the basis of the range of noise environments that may occur on a noise map, the planner identifies three general zones — A, B, and C — to summarize his noise-planning objectives for the community. Zone A would include those noise environments that are potentially hazardous or unsafe in terms of people's hearing. It has recently been established that an exposure of several hours to noise levels of about 75 dB(A) on a daily basis results in some degree of permanent hearing loss in most people *(EPA 1972)*. Zone A would therefore be composed of noise environments having general noise levels of 75 dB (A) or more. These are areas of the landscape that are potentially unsuitable for residential and other noise-sensitive types of development unless buffers of some kind are provided. As a general rule, the planner would restrict zone A landscapes to noisier commercial, industrial, and recreational activities.

Zone B would include those noise environments that are potentially annoying to people residing in them. Some noise-annoyance studies suggest that the first signs of annoyance in persons living in quiet low-density residential neighborhoods are produced by noise levels exceeding 45 dB(A) *(Great Britain Committee 1963, EPA 1972)*. Other studies suggest that annoyance in sensitive (quiet) community areas begins only with noise levels exceeding

Figure 2.—The 1971 noise map for the Town of Burlington aggregated according to three noise-level zones. (It should be noted that had the B zone begun at 55 dBA rather than 45 dBA as shown, the area represented by the zone would have been considerably smaller.)



55 dB(A) *(Kryter 1968)*. Depending on the planner, zone B would therefore be composed of noise environments having general noise levels between 45 or 55 dB(A) and 75 dB(A). These are areas of the landscape that are probably suitable but not always ideal for a range of development types. In general, the planner would allocate higher density housing, industrial parks, recreation uses such as golf courses, and the like to zone B landscapes. The decision to allocate quieter uses to B zones would reflect the overriding quality of other physical and cultural aspects of the landscape.

Finally, zone C would include the remaining noise environments, those that are neither potentially hazardous nor potentially annoying. These are areas of the landscape that are entirely suitable for all types of development. Insofar as possible, the planner would reserve zone C for activities that would not degrade the existing noise environment.

In cases where a planner is interested in assessing a town from several environmental standpoints in addition to that of noise (for example, potential air pollution, flooding, water supply, sand and gravel supply, etc.), the A-B-C noise-zone map that results from this summarization of a noise map may be of even greater planning use than the more detailed noise map from which it is derived (fig. 2).

DISCUSSION

There are three basic features of the noise enviroment assessment methodology that recommend it as a technique for larger scale noise-related land use planning.

First, it requires no measurements and so is practical to use. The only source information required is a land use map and a U.S.G.S. quadrant map or other roadway/topography map (corrected for highway noise characteristics) of the town to be assessed. Although a certain amount of traffic-data collection and digitizing is required, the time/cost involved is small compared to that of multiple on-site measurements and measurement analyses.

Second, the methodology is designed to operate at the community scale. The noise environments comprising an entire community or even a group of communities can therefore be assessed at once. This provides a useful overview of the noise situation and a context for subsequent decision-making.

And third, the effects of any proposed change in land use/highway development on the surrounding noise landscape (changes in noise environments) can be predicted simply by redigitizing the points on the land use or highway noise source maps and the transmission loss may where the change is to occur. Rerunning the program sequence yields a new noise map. In this way, the noise consequences of any land use allocation decision (and its alternatives) can be evaluated before changes in the landscape are actually made.

Each of these features makes the methodology a useful tool for landscape planning and therefore a useful method of noise pollution control. However, as the first noise-environment simulation technique of its kind, the methodology understandably exhibits one apparently significant limitation: it lacks the accuracy provided by site-specific measurements.

Unfortunately, the noise-producing and transmitting characteristics of the landscape do not often easily lend themselves to generalization. For this reason, we have sometimes been forced in our methodology to make assumptions about the noise landscape that do not necessarily represent reality. This is especially true of the assignment of transmission loss values and certain land use noise levels.

The issue of accuracy as a methodological limitation, however, must be considered in light of two important

facts. In the first place, as acousticians acquire more land use noise data and better expressions of transmission loss, these can be easily incorporated into the present assessment procedure.

In the second place, the noise methodology is not designed for smaller scale land use allocation/management purposes. Although better base data are always desirable, the likely noise environments now illustrated by the computer-generated noise map are in all probability quite suitable for the level of decision-making that they are intended to influence.

CONCLUSION

We believe that our environmental noise assessment methodology provides a much-needed basis for large scale land use-related noise pollution evaluation and prevention. We recognize, however, that in the absence of standard noise-environment modelling procedures, numerous assumptions and generalizations were made about the relationship between the production/transmission of noise and certain characteristics of the physical landscape, primarily land use. With the exception of highway noise simulation, no precedent exists for making such generalizations. Those made here represent what is in effect a professional interpretation of available site-specific (measured) noise production and attenuation data. The validity of the assessment methodology is therefore based largely on analogies and inferences made from empirical noise-related research.

This approach to noise tends to be problematic from several points of view. First, the nature of generated and transmitting noise in the outdoor environment is often highly variable. Although various examples of some types of land uses, such as low- and medium-density housing, can be reasonably said to contribute on the average a similar amount of noise to the environment, various examples of other land use types, such as industry, may be responsible for very different amounts of noise output. For example, the difference in the outdoor noise levels generated by a plastics factory and a paper mill may be substantial. Generalizing about the noise output of a land use typed "industry" is therefore likely to underestimate the noise contributions of some industrial land uses while overestimating the noise contributions of other industrial land uses.

The variability in transmitting noise is even more of a problem. Noise in transmission is complexly affected not only by all the elements of the landscape with which it comes in contact, but also by the arrangement of those elements, that is their location and orientation with respect to the noise source area. Furthermore, the degree to which noise is affected by the landscape depends upon the kind of noise that is generated (its predominant frequencies) as well as the areal extent of the source itself. To estimate the effect of a land use noise source on a receiver located some distance away is therefore far from simple.

Second, the body of data pertaining to those aspects of the outdoor noise environment (particularly noise in transmission) which are of interest in noise pollution control is not large. Since generalizations better approximate reality when drawn from numerous observed results, especially where the observed phenomenon is as complex as is noise, this is a fundamental problem.

Third, the lack of pertinent noise data is compounded by the fact that the comparability among investigated situations is low. Different measuring instruments are often used. Different source and receiver conditions are often sampled under still different landscape conditions. Even observed results are sometimes expressed in terms that to the non-engineer appear to bear little resemblance to one another. Drawing

generalizations that can be applied easily to the problem of outdoor noise pollution control is made difficult by these experimental differences.

Finally, among the somewhat comparable noise experiments that have been undertaken, results are at times conflicting. For example, measured reductions of point-source noise in forests range from as little as 1.0 dB/100 feet of vegetation to as much as 7.0 dB/100 feet of vegetation *(Smith 1970)*. Until such experimental discrepancies are explained and resolved, attempts to apply empirical noise data must always be rather frustrating.

Despite these problems, it is felt that the approach taken in formulating the assessment technique presented here is entirely appropriate for and necessary to larger scale noise control planning purposes. In fact, if understood as a preliminary effort to translate observed acoustical data into a usable form for planners and others whose decisions influence the noise environment, we believe our methodology is an extremely valuable noise-planning tool even as it now stands. Without question, however, more empirical noise data and better expressions of landscape noise characteristics are needed, particlularly as regards (1) the noise-producing tendencies of acoustically complex and highly variable land use types such as industry and (2) all aspects of noise in transmission through the landscape. With more observed and comparable results, more representative generalizations about those results can be made.

Greater interaction between planners and accoustical engineers/scientists is therefore warranted. The apparent lack of communication between these professionals to date is responsible for many of the problems described above and encountered in our research. If noise pollution is to be practically controlled in the forseeable future, it is the responsibility of planners to articulate their noise-information needs, while it is the responsibility of acoustical scientists to generate the necessary information and translate it into understandable and easily applied terms.

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ENVIRONMENT AND PHYSICS OF METROPOLITAN AIR QUALITY

A First-approximation Urban-air-quality Indicator

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ABSTRACT.—Development of the first-approximation-urban-air-quality indicator was reported by the Economic Council of Canada. The indicator takes account of ambient concentrations of five pollutants: sulfur dioxide, particulate matter, oxides of nitrogen, carbon monoxide, and total oxidants. Epidemiological evidence indicating the potential impact of these pollutants on human health is also reported. Values of the indicator are calculated for the years 1971-74 for a number of Canadian cities: the overall trend appears to be toward cleaner air, though concentrations of oxidants and nitrogen oxides have increased.

THE CHARACTER OF URBAN CENTERS

DESPITE THE HUMAN TENDENCY to build urban islands of man-made physical environments, our cities are highly dependent upon their interaction with natural ecosystems. In days gone by, cities have always tended to be built in the most productive areas within natural ecosystems. By replacing plant and animal life with asphalt and concrete, houses and factories, and the products and residuals of production and consumption, man has created deserts in which there is minimal natural energy production and maximum human energy use. To fill this gap in net energy requirements, the city spreads its tentacles throughout the ecosystem.

The interaction between the energy-deficient man-made environment and the energy-surplus natural environment is dynamic, and the interface (the "urban confrontation") is often abrupt. The flow of energy and natural resources into the man-made centers and the outflow of man-made products, services, and residuals is continuous, causing a shift in costs and benefits across the interfaces. However, this area of urban confrontation is sufficiently distinct to describe the walls that encase the "fragile bubble-world" referred to by Mowat:

> "When, and if, man comes to regard himself as being in effect an alien entity in the ancient world that formed him, then he will have become the ultimate egomaniac, imprisoned in an infinitely fragile bubble-world of his own contriving — and unquestionably doomed."
>
> Farley Mowat, *Tundra*, McClelland and Stewart, Ltd., Toronto, 1973, p. 13.

Unfortunately, the degree to which human activity affects the remaining elements of the natural environment that exist within cities is still difficult to define and, therefore, to include in

the derivation of an urban environmental quality indicator.

The human population itself is exposed, at least to some extent, to pollutants that it generates; and if we assume that urban populations are (statistically) normally distributed with respect to susceptibility to environmental contaminants, we can see that the population potentially at risk serves as a convenient common weighting factor for aggregating the social impacts of environmental pollutants across urban areas (even though we are aware that air quality can differ greatly from point to point within each area). Because contaminated water can be avoided or rendered safe before use and because North Americans are protected against pollutants that may affect their food (by way of public controls and the availability of a great variety of food stuffs and food sources), the element of environmental pollution most critical to human health is the quality of air that urban populations must breathe. For these reasons the Economic Council of Canada developed its first environmental quality indicator in consideration of urban air quality.

DIMENSIONS OF AIR QUALITY

The popular perception of air pollution is that, if you can see it or smell it, it's "bad." This is, of course, a gross oversimplification: some pollutants, such as carbon monoxide or lead, may be completely undetected by the human senses at typical ambient concentrations. On the other hand, preoccupation with the multitude of elements and compounds that may pose a threat to human life in isolated instances may obscure general trends in air quality.

In constructing our first-approximation-air-quality indicator, the choice of which pollutants to include was largely pragmatic. That is, we included all the pollutants that are measured on a roughly consistent basis in most large urban areas in Canada. These are sulfur dioxide, nitrogen oxides, total oxidants, particulate matter, and carbon monoxide. A sixth pollutant group, total hydrocarbons, was rejected because of imprecise measurement and the absence of generally accepted criteria of safe ambient concentrations.

To provide guidance in our choice of pollutants to be included in the indicator, and also to confirm the choice of pollutant weights (relative severity factors), we undertook a statistical analysis of the relationship between air pollution and health. Weekly average ambient concentrations of the six pollutants mentioned above were related to hospital admissions among the most sensitive members of the population (those under 15 or over 45) for five categories of respiratory disease. In addition, a temperature variable was used to control for seasonal variations. Data were available for the last 41 weeks of 1972 for the cities of Windsor, Ontario, and Edmonton, Alberta.

Hypothesizing a simple linear relationship, we fitted regression equations for each category of respiratory disease by the technique of ordinary least squares. The coefficients, t-statistics, and coefficients of multiple determination (R^{-2}) for selected equations are shown in table 1.

The results, in summary, imply that, indeed, oxidants at levels found in ambient air in several Canadian cities are significant contributors to hospitalization for, in particular, upper respiratory ailments but other categories of respiratory ailments as well; this despite the general Canadian perception that conditions such as those found in Los Angeles are far removed from Canadian circumstances. Likewise, for Windsor, nitrogen oxides and, to some extent, sulfur dioxide air pollutants have some significant bearing on the respiratory well-being of individuals. And the results from our investigation of hospitalization in a third city, Sudbury, Ontario,

Table 1.—Selected regression results

Item	Independent Variables							
	SO_2	COH	NO_x	TOX	HC	CO	TEMP	R^2
WINDSOR, ONT.:								
Upper respiratory	.2	—.5	1.6	2.3	— .3	—2.2	— .2	.42
Infections	(.2)	(—.4)	(1.4)	(1.1)	(— .9)	(—2.0)	(—1.2)	
			2.6	4.0			— .3	.39
			(2.5)	(2.4)			(4.3)	
Pneumonia	1.6	—.1	1.2	1.7	— .4	—1.7	— .1	.37
	(2.2)	(—.1)	(1.1)	(.8)	(—1.3)	(—1.6)	(— .5)	
			2.2	3.4			— .2	.24
			(2.1)	(2.0)			(—2.9)	
EDMONTON, ALTA.:								
Upper respiratory		12.6	40.5	8.3		—4.0	— .1	.22
Infections		(.7)	(.5)	(3.4)		(— .9)	(—1.3)	
				8.9			— .1	.26
				(3.9)			(—1.7)	

Values in brackets are T-statistics.

Table 2.—Correlation coefficients, Windsor, 1972

Item	SO_2	COH	NO_x	TOX	HC	CO	Temp
SO_2	1.0	—	—	—	—	—	—
COH	.42	1.0	—	—	—	—	—
NO_x	— .01	.05	1.0	—	—	—	—
TOX	— .17	.00	.13	1.0	—	—	—
HC	.23	.39	— .40	— .51	1.0	—	—
CO	— .11	— .30	— .11	.38	.01	1.0	—
TEMP	— .39	— .55	— .01	— .10	— .34	.80	1.0

indicate that sulfur dioxide and particulate matter, alone or combined, do not provide a sufficient proxy indicator for all airborne pollutants in that hospitalization for respiratory ailments are not significantly explained by the occurrences of these pollutants. In all, this epidemiological examination lends support to the contention that the traditional concern (sulfur dioxide and particulate matter) must be extended to a wider array of pollutants; an indicator based on several pollutants is not a sufficient proxy for the general quality of urban air. Since, moreover, there are many costs to air pollution other than hospitalization for respiratory ailments, we also reject an air-quality proxy indicator based merely on oxidants, nitrogen oxides, and sulfur dioxide.

Simple correlation coefficients among pollutants (table 2) provide further statistical evidence that the five pollutants included in the indicator cannot be reduced further by using one variable as a proxy for one or more others: only one of these coefficients is as high as 0.5 (although two related to the correlation between pollutants and temperature are also higher than 0.5).

In addition, the literature on the health effects of air pollution provides numerous references to the increased impacts (synergism) that can be expected when two or more air pollutants occur simultaneously; there are, in addition, a few references to decreased impacts. The most notable evidence suggests that particulate matter (particularly small, respirable-sized particles), together with sulfur dioxide, may have an impact greater than the combined impact of both pollutant groups considered separately. Similarly, some

experts treat ozone (oxidants) as a synergistic effect of the presence of nitrogen oxides and hydrocarbons together with sunlight; we have included ozone (oxidants) as a pollutant in its own right although we realize that emissions of the two precursors provide the only policy options for control purposes.

RELATIVE SEVERITY FACTORS

From medical evidence, and from our own epidemiological study, it is clear that, at the same concentration, different pollutants give rise to impacts of differing severity. To take account of this rather obvious fact, the concentration of each pollutant is weighted by a "relative-severity factor."

The relative-severity factor for each pollutant is based on the 24-hour average criterion established by the Ontario Ministry of the Environment, this criterion being the only common time base for which criteria are stated for all five pollutants.

The severity factors are in inverse proportion to the 24-hour criteria; hence total oxidants have the lowest acceptable concentration — 0.03 parts per million — and therefore have the highest relative severity factor —267. Table 3 shows the Ontario criteria and the severity factor for the five pollutants. Note that the scale of the factors is set by arbitrarily denoting the factor for carbon monoxide as equal to one. Finally, since the criteria indicate that one COH has eight times the impact of one part per million of carbon monoxide, the severity factor was determined accordingly without regard for the difference in units of measurement.

CALCULATING THE INDICATOR

The air-quality indicator for any one urban area is a weighted sum of the annual average 24-hour concentrations of the five pollutants and a synergism factor (to be discussed shortly). The annual mean concentration is multiplied by the relevant severity factor; the products are labelled "impact units per capita," and they can be added to yield a "city-pollution index." These calculations are depicted schematically in figure 1.

The synergistic impact of sulfur dioxide and particulate matter is assumed to be limited by the lesser occurrence of either one or the other pollutant. Consequently, as shown in figure 1, this factor enters the calculation of the city-pollution index (CPI) as the lesser of the value of the impact units per capita for these two pollutants; it is not directly calculated from any ambient air concentration data.

The CPIs are roughly comparable from city to city and provide relative, not absolute, descriptions of urban air quality between cities and over time in any one city. For public policy purposes, the latter time series is very useful not only because it gives a gross picture of air-quality changes, but because it reflects, from its component parts, the possible impacts of air pollution on the population; clearly, such information will suggest control priorities that might provide substantial benefits

Table 3.—Relative severity factors

Pollutant	Units	Ontario 24-hour criteria	Relative-severity factor
Carbon monoxide	ppm	8.00	1
Nitrogen oxides	ppm	.10	80
Oxidants	ppm	.03	267
Sulfur dioxide	ppm	.10	80
Particulates	coefficient of haze per 1,000 ft. of air	1.00	8

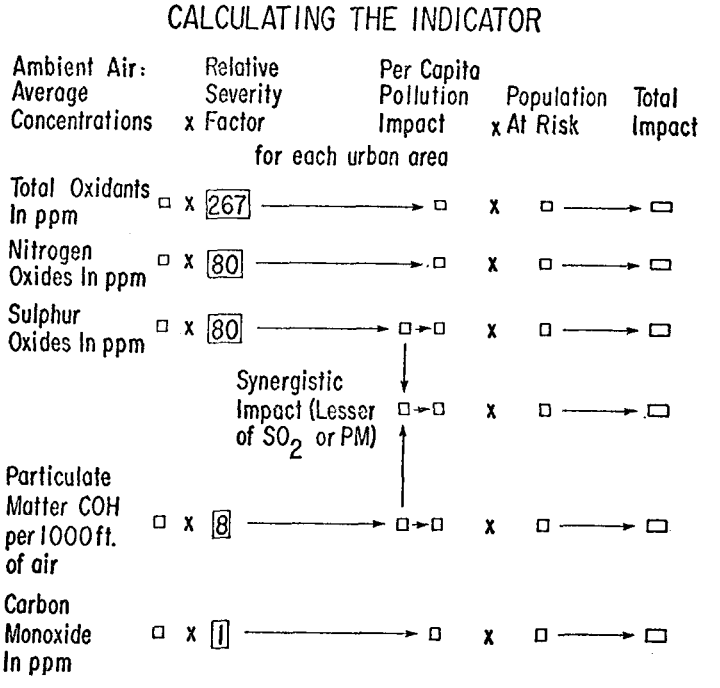


Figure 1.—Calculating the indicator.

—not merely a nebulous statement about the weight or volume of different pollutants in ambient air.

The impact units per capita for each pollutant and synergism are multiplied by the population potentially at risk to yield what we call "impact units." These products are added, by pollutant, for all cities in the sample to yield an "urban pollutant sub-indicator" which provides a comparison, over all cities combined, of the *relative* importance of each pollutant, in any one year, and, when measured over several years, of the emerging or diminishing importance of each pollutant group in respect of all citizens living in all urban areas considered in the compilation of the indicator.

The sum of the urban pollutant Sub-indicators, including synergism, is defined as the "urban air-quality indicator."

The first-approximation-air-quality indicators are, in fact, *social* indicators in that, if all the pollutants had the same annual average concentration in 1975 as in 1974 (and given the constant relative severity factors) and at the same time the population of the cities increased, all urban pollutant subindicators would increase in 1975, implying a fall in the quality of life, in respect to the air environment. In other words, the quality of life (at least in respect to this one aspect of reality) is improved if individuals move from areas of high air pollution to areas of relatively low air pollution, and the converse would also hold; not an unreasonable assumption in our estimation.

Of course, the purpose of improving the quality of life could be more effectively, and probably more economically, achieved by reducing the emissions and thereby the concentration of airborne pollutants. One might note also that dispersion of emissions (by high stack and/or escape-velocity management) could also lower the pollutant subindicators, provided that the pollutants do not

merely fall out on some other urban area included in the indicator. This, at one time, implies that dispersion can provide a means to improve urban living standards and yet, that it can only be seen as a partial solution; ideally the compilation of the indicator will be extended to all urban areas (and to rural population where the risk is high). Likewise, as the implications of the impact of air pollution on the nonhuman elements of the environment are incorporated into the relative-severity factors, the inclusion of air-pollution data from rural areas may render the strategy of dispersal less effective in lowering the value of the pollutant subindicators.

Imposing urban-generated costs on the rural portion of the same or other ecosystems of which the city is merely a part, can, and eventually must, reduce the benefits the city and its population must obtain from the countryside.

Finally, like the gross indicators of economic activity (gross national product, price indices, unemployment rates, etc.), the generality of the urban-air-quality indicator provides little more than a glimpse of reality; like its counterparts, however, it can provide comparisons with previous time periods and therefore can generate public and political interest in delving deeper into its component parts and distributional aspects.

SOME RESULTS

The urban-air-quality indicator has been calculated for the years 1971-74 and is plotted on the upper portion of

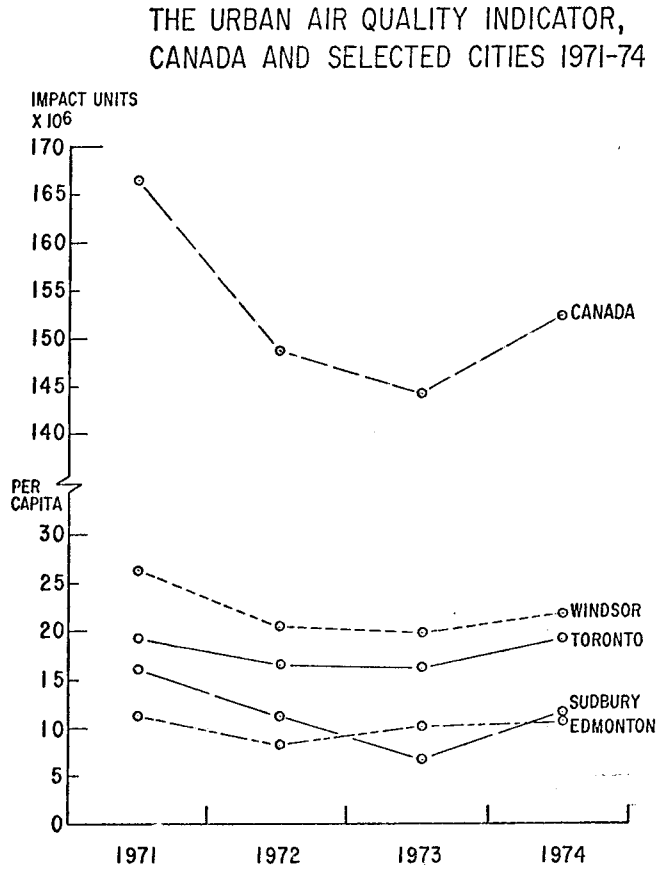


Figure 2.—The urban air-quality indicator, Canada and selected cities, 1971-74.

figure 2. As the graph shows, the indicator fell substantially between 1971 and 1973, reflecting improved air quality. In 1974, however, the indicator rose again, but remained below the 1971 level. In the absence of large population movements over this period, these trends can be attributed directly to changes in ambient concentrations of the pollutants measured.

City pollution indices for four representative urban areas are plotted on the lower portion of figure 2 (the indicator includes data from 11 Canadian cities). With the exception of Edmonton, these cities reflect the national trend of improved air quality through 1973, worsening by various degrees in 1974, the most dramatic reversal taking place in Sudbury.

Further disaggregation, by pollutant, reveals the nature of the decline in air quality in 1974. Figure 3 compares the 1971 and 1974 levels of the pollutant sub-indicators, totalled across the 11 cities. Reflecting traditional concern for air quality in terms of the popular pollutants, and the resulting decline in ambient levels by abatement and dispersion, the indicators for carbon monoxide, sulfur dioxide, and particulate matter have all declined substantially over the 4-year period. The new pollutants, oxidants and oxides of nitrogen, on the other hand, have increased considerably. Since oxidants are formed by photochemical reactions in the atmosphere, for which nitrogen oxides are a necessary input, the increase in ambient concentrations of these two pollutants can probably be explained in terms of emissions of the latter alone.

Nitrogen oxides are one of the products of fuel combustion: if the flame temperature is high enough, atmospheric nitrogen is oxidized. A nationwide inventory of pollutant emissions compiled by the Federal Department of the Environment for 1970 reveals that motor vehicles accounted for some 58 percent of total NO_x emissions, and that stationary combustion such as power generation and incineration accounted for most of the remainder (34 percent of the total).

One can speculate, therefore, that the increase in the subindicators for oxidants and nitrogen oxides reflect the

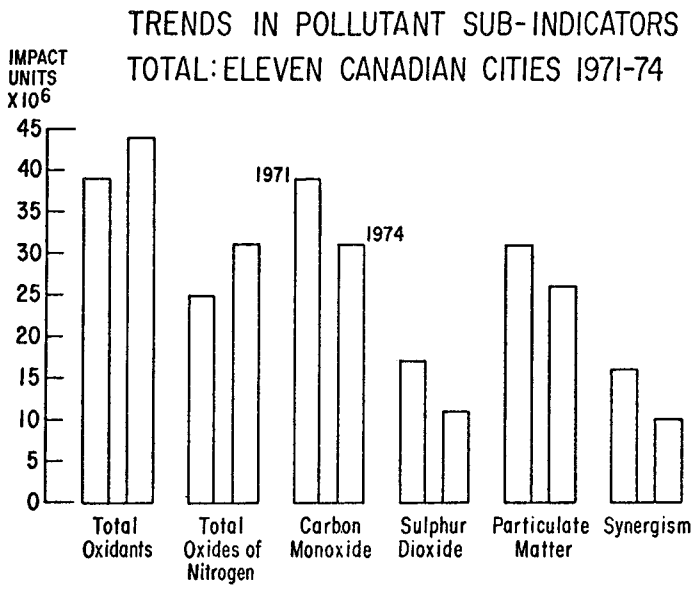


Figure 3.—Trends in pollutant subindicators, eleven Canadian cities 1971-74.

increase in the urban automobile population and the relative lack of control of NO_x by new-car emission standards, at least prior to 1973. The effect of exhaust gas recirculation, first used on some 1973 models, will not significantly reduce NO_x concentrations until these cars make up a significant portion of the automobile age structure.

As a final note on the analytical utility of the indicator, we should point out its "first-approximation" nature. The indicator will be subject to continual modification and improvement as more and better data become available. Specifically, for 1975 and beyond, the indicator will be reformulated, if possible, to consider ozone (as opposed to total oxidants), nitrogen dioxide (versus total oxides of nitrogen), and specific size and chemical descriptions of particulate matter (replacing the coefficient of haze measurements). Finally, the more accurate chemiluminescence technique is coming into wider use for measuring ozone and nitrogen oxide, imparting greater precision to the indicator.

OBJECTIVE OF SOCIAL AND ENVIRONMENTAL INDICATORS

Why have an indicator of air quality in urban centres at all? To repeat some points raised earlier:

- The urban confrontation with the natural environment tends to be abrupt to the point that the air environment is something different from the natural environment in which mankind developed over thousands of years;
- This different environment may have adverse effects on the population that resides in the urban bubbles, and this population represents the bulk of the total population;
- And therefore, if our interest is the maintenance or improvement of the quality of human life, we should have some general information on how this one aspect of the total reality is changing, information that is easily understood by the society and its political leaders.

If the indicator is changing, we (individuals, society, and the decision-makers) will want to know what *controllable* factors are influencing the change and what the distributional aspects of these changes are. This the indicator and its sub-indicators can do. The simplicity of the indicator is "on purpose;" its lack of precision and sophistication makes it meaningful to the *public*, and yet it does not preclude more detailed analysis — it may even encourage it. Finally, one may be critical of the fact that it is a relative measure of air quality rather than a statement of absolute quality — that is, it does not say that at a value of, say, "X" things are "bad," that at "X-Y" things are "good," and that at "X+Y" things are "terrible." Why do we not venture into the debate of absolute air quality? Precisely because air quality is but one part of environmental quality as a whole, and environmental quality is but one aspect of the quality of life as a whole.

Let us emphasize one point. Since the materials that enter production and consumption must equal, in terms of mass, the material content of the products we manufacture and the residuals we generate (less that portion that is recycled), we should be aware that the residuals that are removed from waste gases may simply be reflected in an increase in residuals that we release into the water and land resources of the planet. Quite obviously the net environmental impact of such a transformation may be greater than, equal to, or less than that associated with the equivalent mass of air pollution. Let us ask then, "Which of us can say, *a priori*, that a reduction in air pollutant exposure is automatically a good thing in the wider context of environmental quality and the quality of human life?"

An urban air-quality indicator describes one aspect of the fragile bubble world of the urban scene, but it should be sufficient evidence that man creates unnatural microenvironments. We must all be prepared to examine the viability of this human milieu lest the bubble burst.

Use of a Land-use-based Emissions Inventory in Delineating Clean-air Zones

by VICTOR S. FAHRER *and* HOWARD A. PETERS, *respectively research associate, Department of Landscape Architecture and Regional Planning; and associate professor, Department of Public Health, University of Massachusetts, Amherst, Mass.* *This study was supported primarily by the University of Massachusetts Agricultural Experiment Station (Paper No. 1063). Additional support was received from the U. S. Department of Interior Office of Water Resource Research and the Northeastern Forest Experiment Station, through the Pinchot Institute for Environmental Forestry Studies.*

ABSTRACT.—Use of a land-use-based emissions inventory from which air-pollution estimates can be projected was studied. First the methodology used to establish a land-use-based emission inventory is described. Then this inventory is used as input in a simple model that delineates clean air and buffer zones. The model is applied to the town of Burlington, Massachusetts. Conclusions and recommendations are offered for the model's use and for interpretation of its results.

THE PURPOSE OF THIS paper is to explore the possibility of using a land-use-based emissions inventory for delineating clean (and polluted) air zones. In this inventory the emission data were averaged and not derived from on-site measurement.

The compiling of this inventory is a two-step process. First a local emissions inventory must be obtained, usually through the federal or state air pollution office. These data will be in the form of amount per time (tons/year) for specific pollution sources. The next step will be to correlate the emissions inventory with a land-use-classification system (MacConnell's land - use - classification system for Massachusetts, 1973). The output of this combination will yield data in the form of amount per area per unit time (tons/acre/year) for each land-use class.

What we are proposing, then, is a land-use-based emissions inventory from which concentration calculations can be made and buffer zones established by using an appropriate dispersion model.

Our particular research project was part of a larger effort devoted to developing the Metropolitan Landscape Planning Model—METLAND *(Fabos 1973)* at the University of Massachusetts. This model inventories and quantitatively assesses a study area in terms of development suitability, resources of special value, and potential for hazards (including air pollution).

The METLAND Model required the assessment of air quality on several scales: regional, town, and site. This was accomplished by using data from the land-use-based emissions inventory as input to three adopted models: Miller and Holzworth *(1967; also Holzworth 1972)*, Hanna *(1971)*, and Turner *(1970)*. For brevity, only the methodology based on Turner will be described here.

OBJECTIVES

The specific study objectives were to: (1) compile a land-use-based emissions inventory as a data base for concentration calculations and (2) adopt a model or technique to convert emissions into concentrations. The procedure was then applied to the METLAND study area of Burlington, Wilmington, and Tewksbury, Massachusetts, three towns in the metropolitan Boston area.

PROCEDURE

Land-Use-Based Emissions Inventory

The procedure for establishing a land-use-based emissions inventory is shown (fig. 1) and the steps explained in the following sections. In the original study, the entire Commonwealth of Massachusetts was inventoried; however, only the Metropolitan Boston Air Pollution Control District (APCD) is referred to here.

After a land-use-based emissions inventory was established, a model was developed to use that data for delineating clear air (buffer) zones around area sources.

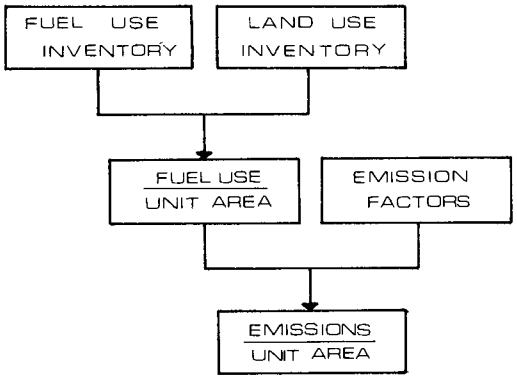
Fuel-Use Inventory

As in 1970, Walden Research Corp. was contracted by the Massachusetts Bureau of Air Quality Control to conduct an emissions inventory for the entire Commonwealth for base year 1972. As before, each APCD was to be inventoried and the totals added to produce an emissions inventory for the entire state. However, at the time (January 1975), only the fuel-use inventory and allocation procedure were completed.

This information was available in a preliminary draft *(Walden, n.d.)*, and the fuel-use inventory (including non-fuel emission data) for area sources was available on computer printouts, both supplied by the Bureau of Air Quality Control. Therefore, we applied the emission factors.

It should be noted that for two important sources of pollution, data were unobtainable: electric generating plants and industrial process emissions. Accordingly, they were not represented in the final emissions inventory. Allowances for these omissions will be explained later. Also of note, the 1972 data were applied to METLAND base year 1971, the year of the last land-use inventory by MacConnell.

Figure 1.—Procedure for establishing a land-use-based emissions inventory.



Land-Use Inventory

William MacConnell *(1973)* inventoried the land use for the Commonwealth of Massachuetts in both 1952 and 1971. This involved aerial photography of the State and interpreting those photographs via a land-use classification system. Then land-use maps were made from the results, and the total number of acres of each land-use class were tabulated for each town and county. This was the land-use system already incorporated into the METLAND model.

Not all the individual land-use classes were needed for the Air Quality Submodel, so these were aggregated according to the Walden draft (table 1). Next, the total number of acres of each aggregate land-use type was tabulated for the Metropolitan Boston APCD for 1971.

Fuel Use/Unit Area

A matrix of aggregated land-use class versus itemized fuel use was constructed for the Metropolitan Boston APCD. The units of this matrix were derived by dividing the amount of a given fuel consumed for a given land use by the number of acres of that land use. Other emission parameters were also treated, such as the number of forest fires/acre of "other" land and the number of landing-takeoff cycles/acre of "airport" land.

The allocation of fuel use and other emission parameters to the land-use

Table 1.—Aggregation of MacConnell's Land-Use Classes

Description* (number of individual land-use types)	Aggregated land-use class code
Low-density residential (6)	URL
High-density residential (3)	URD
Commercial (3)	UC
Industrial (3)	UI
Divided highway (1)	HW
Airports (1)	UTA
Railyards (1)	UTR
Freight and bus terminals (1)	UTT
Docks and waterfront warehouses (1)	UTW
Urban open land (3)	RO
Outdoor recreational facilities (15)	RO
Mining or waste-disposal areas (5)	RO
Agricultural and open lands (11)	Other
Forest lands (40)	Other
Wetlands—except open fresh water (10)	Other
Open fresh water (1)	W

*For complete descriptions, see MacConnell *(1973)*.

Table 2.—1971 Annual Emission Rates/Acre: Metropolitan Boston APCD

[In lb/yr-acre]

Land use	Pollutant				
	TSP	SO_2	NO_x	CO	HC
URL	10.2	16.8	73.3	525	98.7
URD	281	460	1,950	14,900	2,790
UC Area	1,120	5,080	5,590	15,100	5,490
UC Area + Point	1,210	5,690	5,920	15,100	5,510
UI Area	1,560	3,530	4,560	15,700	9,610
UI Area + Point	2,030	5,300	5,550	16,000	9,750
HW	177	57.4	2,380	8,630	1,970
UTA	238	173	2,730	18,300	2,980
UTR	177	58.3	1,800	14,900	2,600
UTT	184	71.6	1,990	15,000	2,620
UTW	486	2,770	3,830	15,500	3,120
RO	.588	.977	7.81	17.6	4.44
Other	1.25	1.41	8.37	14.3	4.86
W	NIL	.267	.276	138	46.0

classes was made according to the Walden draft and the EPA's APTD-1135 *(1973a)*. Two sets of figures were used for industrial and commercial land uses. One for fuel use by area sources only and the other for fuel use by both area and point sources (those emitting 100 tons/year of any pollutant).

Application of Emission Factors

Using AP-42 *(EPA 1973b)*, emission factors were applied to the values in the fuel-use matrixes to determine amount of pollutant/acre from all sources for the five primary pollutants, total suspended particulates (TSP), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), and hydrocarbons (HC) for all land-use classes.

Emissions/Unit Area

Emissions/acre of the five primary pollutants for all land-use classes in the Metropolitan Boston APCD were summed and the totals listed (table 2).

As mentioned previously, electric

generating plants were omitted from the inventory. This omission was not accounted for because few towns (incluing the study area) have these plants, and because adding these emissions into the inventory would skew the emissions/acre of industrial land, especially for SO_2, making the value too high for typical applications.

Industrial-process emissions were also omitted. Upon checking the previous Walden inventory for 1970, we concluded that such emissions were insignificant, being less than 10 percent of the industrial emissions for any one pollutant.

A MODEL FOR THE DELINEATION OF CLEAN AIR ZONES FOR AREA SOURCES

The establishment of a buffer zone around a high polluting area source will insure that the concentrations of all pollutants (from the source) beyond this zone will be within prescribed standards. Although concentrations may exceed standards within the zone, land use there would be limited to little or no human activity. The method assumes that the area source is the only significant source of pollution in the surrounding area (encompassing about a 2-mile radius around the area source); therefore this method is more applicable to proposed high polluting sources such as industrial and commercial areas. Also, this method is more suitable for somewhat square-shaped area sources. Industrial and commercial point sources those emitting 100 tons/year of any pollutant) should be modeled separately.

General Equation

The basic equation used to determine clean air (buffer) zones is described by Turner *(1970)*. It simulates a square-shaped area source as virtual point source. The concentration at ground level along the centerline of the plume for downwind distance x an effective stack height H is given by:

$$C = \frac{Q\ (10^6)}{\pi\ \sigma_y \sigma_z\ u} \exp\left[-\tfrac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]\left(\frac{Tk}{Ts}\right)^{.20} \quad [1]$$

Where:

- C = Concentration ($\mu g/m^3$)
- Q = Emission rate (g/sec)
- 10^6 = ($\mu g/g$), converts grams to micrograms
- $\sigma_y\sigma_z$ = Standard deviations of the concentration distributions (m); determined by x for each stability class
- u = Wind speed (m/sec)
- H = Effective stock height (m)
- Tk = Sampling time for which equation is valid (3 min)
- Ts = Desired sampling time (min)

The term $\left(\frac{Tk}{Ts}\right)^{.20}$ is a reduction factor for sampling times greater than 10 minutes. This reduction is due primarily to wind meander over longer periods of sampling time.

If equation 1 is transformed by dividing both sides by Q, then C/Q versus downwind distance (x) can be plotted for various acreages of area sources. The variables in the equation are determined by the certain standard being modeled and by the assumed meteorological conditions associated with that standard.

Governing Pollutant Standard

Upon analyzing the emission rates of the pollutants and their related federal standards, we determined that the secondary 24-hour standard of 260 $\mu g/m^3$ for sulfur oxides, SO_x (measured as SO_2), was the most likely to be exceeded. Therefore, if a buffer zone were established based on this standard for SO_2, then the buffer zone should also be adequate protection from all other area source pollutants (except perhaps oxidants).

Governing Dispersion Conditions

When determining the width of a buffer zone it is usually desirable to use "worst-case" conditions to ensure an adequate margin of safety. The following variable values represent worst-case 24-hour conditions with respect to dispersion meteorology and emission rates.

The values of σ_y and σ_z at a given distance depend upon the stability of the atmosphere. The worst case conditions of stability are class D in the day and class F at night *(Turner 1970)*. These classes were approximated by using class E stability for 24 hours.

The lower the wind speed, the higher the resultant concentrations; however, the lowest common windspeed associated with stability classes D, E, and F is 2 m/sec.

The effective stack height, H, is the total height of pollutant release. This being the sum of the physical stock height plus the plume rise due to the vertical velocity and buoyancy of the released pollutant. The value of H was assumed to be 20 meters (m) in all cases.

The sampling time, Ts, is 24 hours, making the reduction factor $\left(\frac{Tk}{Ts}\right)^{.20}$ = 0.37.

The wind was assumed to meander in accordance with the reduction factor. The buffer zone width was to be determined irrespective of wind direction; therefore the buffer zone would encircle the entire area and be of a constant width.

Specific Equation

When the worst-case values are substituted into the transformed general equation it becomes:

$$C/Q = \frac{(10)^6}{(3.14)\,\sigma_y\sigma_z\,(2)} \exp\left[-\tfrac{1}{2}\left(\frac{20}{\sigma_z}\right)^2\right](.37) \quad [2]$$

Now the only remaining variables are σ_y and σ_z which depend upon downwind distance (x). Values σ_y and σ_z from Turner *(1970)* were used.

Graphical Representation of C/Q

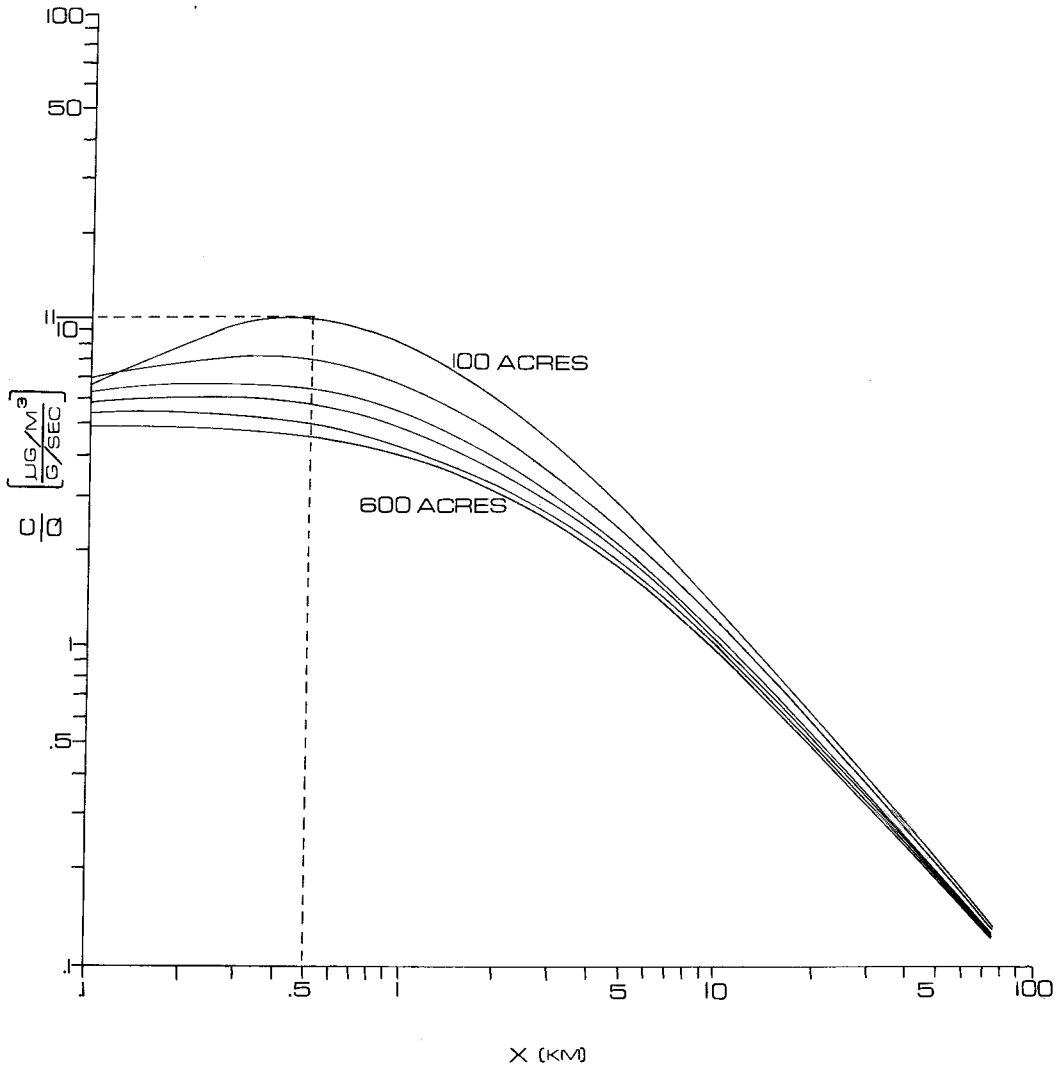
A graph of C/Q versus distance from the edge of the source can be plotted for various acreages. Such graphs (on log-log scales for clarity) were plotted for acreages of 100 to 600 acres (fig. 2).

Determination of Emission Rates

The next step in the procedure was to determine emission rates/acre for SO_2, which when multiplied by the number of acres of the source, and that product multiplied by an appropriate C/Q factor, would yield concentration. The worst emission rates occur on cold days when space heating is at a maximum. For the Metropolitan Boston APCD, the average coldest-day temperature, −10°F (−23°C), occurs in January. However, the chance of the coldest day and worst dispersion conditions coinciding were felt to be rather minimal. A more likely situation would have the worst dispersion conditions occurring on an average cold day of 30°F (−1.1°C). Emission rates were made based upon both temperatures.

To determine 24-hour emission rates/acre for sources having space heating emissions, a method was developed to separate these heating emission from the other daily combustion emissions. By estimating the annual amount of fuel consumed for space heat (the assumption being that this percentage is the same for emissions of space heating) and deducting this from the annual total fuel consumed, the remainder was attributed to fuel consumed for processes. One recent study *(Stanford Research Institute 1972)* gave the following percentages of total energy consumed that was used for on-site space heating in the U.S.:

Figure 2.—C/Q vs. distance from area source.



	Percent	
Residential	79	
Commercial	73	
Industrial	7	(estimated)

To make these figures more representative of the Metropolitan Boston APCD, these percentages were modified with respect to the number of annual degree heating days for the APCD compared with the national average. (Note: The number of degree heating days/day is equal to the number of degrees the average temperature for that day was less than 65°F). The number of annual degree heating days for the Metropolitan Boston area was estimated to be 6300 *(Environmental Science Service 1968)*, and the corresponding figures for the U.S. is 4600 *(Landsberg et al. 1963)*. The modification formula became:

$$Pm = \frac{P \times \left(\frac{6300}{4600}\right)}{P \times \left(\frac{6300}{4600}\right) + (100\text{-}P)} \qquad [3]$$

where:

Pm = modified percentage of space heat emissions
P = unmodified U.S. average (both terms expressed as percent)

The modified percentage space heat emissions are:

	Percent
Residential	84
Commercial	79
Industrial	9

Annual space-heating emissions could be determined for a land-use class by first multiplying the total fuel combustion/acre (from the emissions inventory) by the appropriate space-heat percentage. Annual process emissions/acre include the remaining fuel combustion emissions plus annual process losses (estimated from *Morgenstern 1972a, 1972b)*, incineration, and mobile source emissions (table 3).

To obtain a daily emissions rate/acre, first the annual space heating figure (if one existed) was multiplied by the ratio of the number of degree days for that day over the annual total number of degree days. Then the process annual figures was divided by the number of operating days/year. The number of operating days/year were based on the following estimates:

Industry	288 days/year
Commercial	288 days/year
Residential	366 days/year
(inventory was taken on a leap year)	
All other land-use classes	366 days/year

Finally the space heat and process figures for each land use were summed and converted to the metrics of the model, g/sec-acre (table 4).

Table 4.—Emission rates/acre at —10°F and 30°F

[In g/sec-acre]

Land use	Temperature	
	—10°F	30°F
URL	0.000920	0.000450
URD	.0252	.0124
UC Area	.267	.135
UC Area + Point	.300	.152
UI Area	.0775	.0675
UI Area + Point	.116	.102
HW	.000823	.000823
UTA*	.000843	.000843
UTR	.000836	.000836
UTT	.00103	.00103
UTW	.0397	.0397
RO	.0000140	.0000140
Other	.0000768	.0000377
W	.00000383	.00000383

*Uses Berkshire APCD data so as not be skewed by Logan International Airport in Boston.

Table 3.—Annual space heat and process emissions

[In lb/yr-acre]

Land use	Total process					
	Combustion		Process losses	Incineration	Mobile sources	Total
	Space heat	Process				
URL	11.8	2.2	—	—	2.8	16.8
URD	386	17	—	—	57	460
UC Area	3,960	1,050	—	10	60	5,080
UC Area + Point	4,440	1,180	—	10	60	5,690
UI Area	300	3,030	—	140	60	3,530
UI Area + Point	440	4,480	100	220	60	5,300
Other	1.18	.23	—	—	—	1.41

For some industries, especially those involved primarily in research and development, a 9-percent allotment for space heating emissions may be too low. These industries might be better modeled by considering them as commercial sources.

Use of the Model to Determine Buffer-Zone Width

The procedure for determining buffer-zone width is quite simple. The values needed to find the width (x) are the concentration (C), emission rate/acre, and number of acres of the source. Then the C/Q ratio can be determined and the value of x obtained from the previously plotted graph (fig. 2).

The value of the concentration cannot be input as 260 $\mu g/m^3$, the secondary 24-hour standard for SO_2 but must be modified because the ambient temperature is not at standard conditions (25°C = 298°K). To obtain standard temperature correction, a sampled concentration is multiplied by the ratio of ambient temperature (°K) to standard temperature (298°K). Therefore, to find the concentration at −10°F (−23°C, 250°K) that would be equal to a concentration of 260 $\mu g/m^3$ at 25°C, 260 $\mu g/m^3$ must be multiplied by $\frac{298°K}{250°K}$. The modified standard concentration becomes 310 $\mu g/m^3$. The same modification can be made for a temperature of 30°F (−1.1°C, 272°K), yielding a concentration of 285 $\mu g/m^3$.

The same case for modifying temperature can be made concerning pressure; however, normal changes in pressure do not produce significant changes in concentration.

To determine Q, the size of the study area in acres is multiplied by the appropriate emission rate/acre for either −10°F or 30°F.

By dividing 310 $\mu g/m^3$ by Q at −10°F, the buffer-zone width can be determined by using the graph and interpolating, if necessary, between acreage lines. If the C/Q value is greater than any C/Q value on the graph for that acreage, then no buffer zone is required. If a buffer-zone width is obtained from the graph, it can be mapped as a continuous swath around the entire area source. This process can be repeated, using 285 $\mu g/m^3$ and Q at 30°F. Since this emission rate/acre is less than that at −10°F, this buffer-zone width (if one exists) will be smaller.

The outer edge of the −10°F buffer zone represents the zone of no potential hazard from air pollution (except possibly from oxidants and significant line sources.) From the outer edge of the −10°F buffer zone to the outer edge of the 30°F buffer zone represents an area of slight potential hazard. All land within the 30°F buffer zone plus the area source represents a major potential air-pollution-hazard zone.

These zones represent *potential* hazard areas, since emissions were based on average data for the entire APCD. Such zones may be used to site sampling stations for obtaining actual concentrations.

Critical Sources and Acreages

Within the range of acreages considered (100 to 600 acres) only industrial and commercial classes produced enough emissions to exceed the equivalent secondary 24-hour standards. Through an iterative process, the minimum acreages that produce concentrations that exceed the standards were determined (table 5).

The use of this model is illustrated by an application to an area source in the METLAND study area.

APPLICATION

A commercial area source of 105 acres in Burlington was used as an example.

At −10°F, the value of Q became:

$$Q = .267 \text{ g/sec-acre} \times 105 \text{ acres} = 28.0 \text{ g/sec} \quad [4]$$

making the value of C/Q:

Table 5.—Critical area sources

Land use	Temperature (°F)	Critical acreage	Buffer-zone width (km) for the following acreages:					
			100	200	300	400	500	600
UC Area	—10	100	0	1.4	2.1	2.9	3.8	4.7
	30	300	0	0	0	.70	1.1	1.4
UC Area + Point	—10	50*	.70	1.6	2.5	3.5	4.5	5.5
	30	250	0	0	.65	1.1	1.6	1.9
UI Area	—10	800*	0	0	0	0	0	0
	30	>1,000*	0	0	0	0	0	0
UI Area + Point	—10	450	0	0	0	0	.32	.65
	30	500	0	0	0	0	0	.48

*Values were obtained by extrapolation.

$$C/Q = \frac{285\ \mu g/m^3}{14.2\ g/sec} = 20.1 \frac{ug/m^3}{g/sec} \quad [5]$$

From the graph for 100 acres (fig. 2, dashed lines), if $C/Q = 11 \frac{\mu g/m^3}{g/sec}$, then x = .5 kilometers from the source, meaning a .5 kilometer buffer zone (fig. 3).

At 30°F, the value of Q became:

$$Q = .135\ g/sec \times 105\ acres = 14.2\ g/sec \quad [6]$$

$$C/Q = \frac{285\ ug/m^3}{14.2\ g/sec} = 20.1 \frac{ug/m^3}{g/sec} \quad [7]$$

Such a value exceeds those on the graph for 100 acres; therefore no buffer zone is required under these conditions.

CONCLUSIONS AND RECOMMENDATIONS

The threat of a hazard is so slight for the —10° buffer zone that all land uses and activities, except those for critical receptors, can occur there. However, caution should be taken not to group together too many high-polluting land uses of critical or near-critical acreage. Land within the 30°F buffer zone should be of strictly limited land use, with no additional activity planned within the actual buffer zone. The buffer zone should consist of pollutant-resistant vegetation. The possibility of direct source controls within the area source should be investigated.

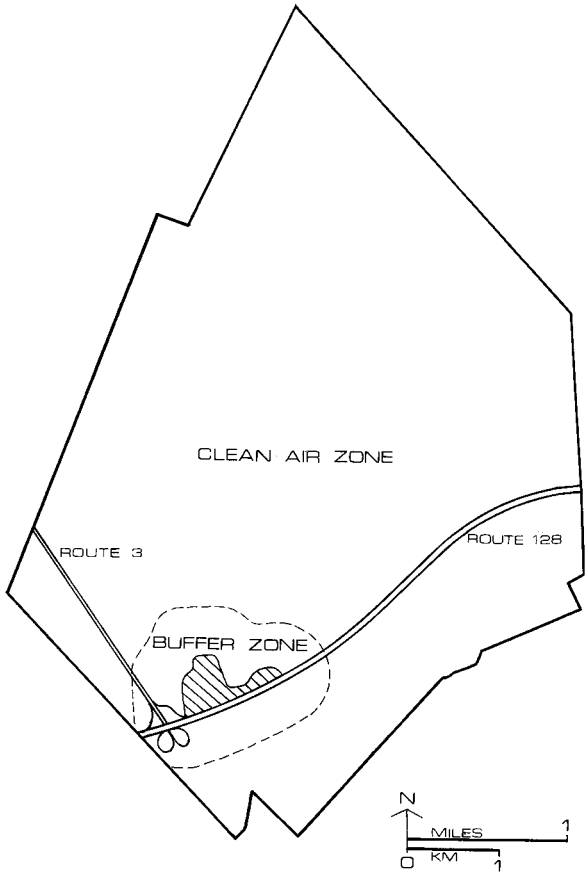
All of the above recommendations are made in the absence of actual air-sampling data. Planning decision may be changed should sampled concentration data become available.

This model and the data generated for its use are better suited for future planning of developable land; however, it can still be applied to existing area sources. Point sources emitting over 100 tons/year should be evaluated separately. If a potential hazard zone should be found, the next step should be the acquisition of specific emission data for recalculation of the model and/or on-site monitoring of air quality. Then, if warranted, a control strategy can be decided.

Of great use to this model would be a correlation of stability, wind speed, wind direction, and temperature with daily concentrations. This could be used to validate the governing conditions assumed in the models. There was not enough time to undertake that task, but such correlation data would be invaluable to these models, and to other models based on 24-hour (or other short-term) standards.

Finally, the process of using empirical data and a simple model offers the planner a relatively fast and noncomplex method of generating air quality information. This process is especially useful in instances where observed data are not available. However, the planner

Figure 3.—Clean air and buffer zones: Burlington, 1971.



must remember that the results are tentative and should be regarded as such.

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Application of the Urban Mixing-depth Concept to Air-pollution Problems

by PETER W. SUMMERS, *chief, Atmospheric Dispersion Division, Atmospheric Environment Service, Environment Canada, Toronto, Canada.*

ABSTRACT.—A simple urban mixing-depth model is used to develop an indicator of downtown pollution concentrations based on emission strength, rural temperature lapse rate, wind speed, city heat input, and city size. It is shown that the mean annual downtown suspended particulate levels in Canadian cities are proportional to the fifth root of the population. The implications of this and other results of the model are discussed.

A LARGE AND INCREASING proportion of the population of North America lives in large cities. Thus by far the largest time-integrated exposure of people to air pollution occurs in urban areas. In spite of improved pollution-control technology, the continued growth of cities and especially of vehicular traffic suggests that there will be no near-term decrease in this exposure. To make rational choices between various land-use and pollution-control strategies, decision - makers require informaton about how the dstribution of emissions and meteorological factors combine to affect urban air-pollution concentrations.

This information can be generated in many ways and can be provided in a wide array of formats. For example, numerical modelling techniques can simulate the ground-level pollution concentrations over the whole city for any given set of source configurations and several typical sets of meteorological conditions. Whilst such results have many valuable uses, they require very detailed source-emission inventories and meteorological data on space and time scales that are usually not available. On the other hand, a simple approach, which gives the pollution concentration in the centre of a city in terms of the major causative factors, also is valuable for urban planners.

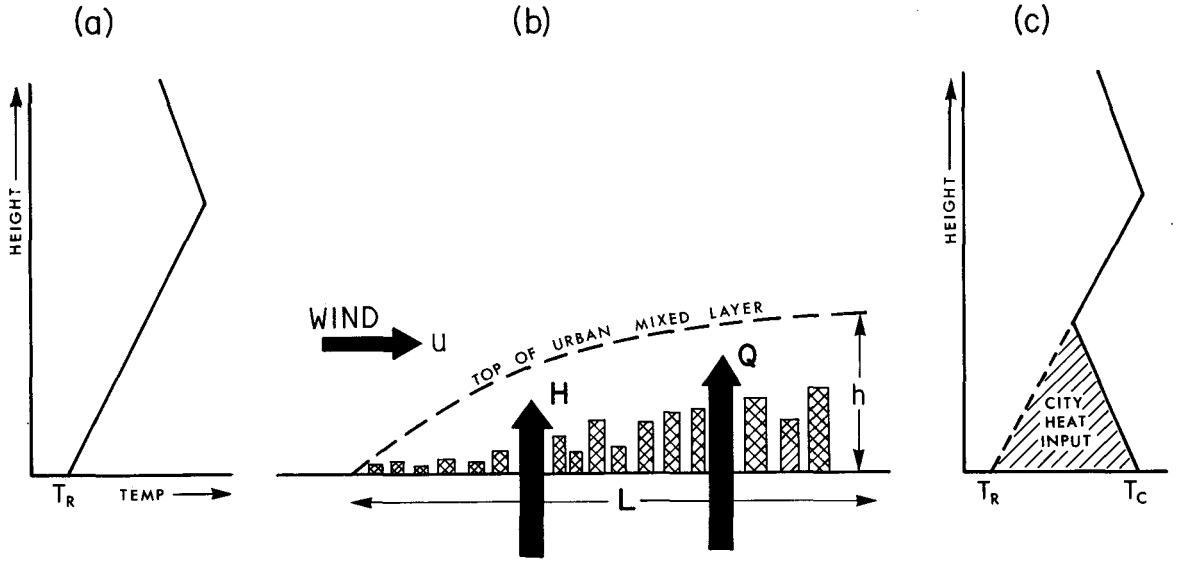
In this paper the simple urban heat-island model developed by Summers *(1965)*, using the mixing-depth concept, will be extended to develop an urban pollution indicator in terms of several easily understood and measurable parameters. Some of the implications of this indicator will be discussed—especially in relation to city size and energy use.

THE HEAT-ISLAND MODEL

The phenomenon of the "urban heat island," where night-time surface temperatures on clear nights with light winds are considerably higher in urban areas than in surrounding countryside, has been observed for over 100 years and has been documented extensively in the last 50 years. The most recent comprehensive review on the subject is by T. R. Oke *(1974)*. However, a physical model that could satisfactorily explain the general features of the heat island was not developed until relatively recently *(Summers 1965)*.

The basic concept of this model is shown schematically in figure 1. On clear nights with light winds (<5 m sec^{-1}), a surface-based temperature inversion usually develops in rural areas (that is, the temperature increases with height above the ground). The difference between this vertical temperature profile and the dry adiabatic lapse rate

Figure 1.—Schematic representation of the development of the urban mixed layer. (a) The vertical temperature profile upwind of the city with a surface-based inversion. (b) The development of the mixed layer due to urban heat input as air moves from left to right. (c) The vertical temperature profile modified by the city to produce a ground-based unstable layer.



(a temperature decrease of 1°C per 100 m of height, which normally occurs in the lower atmosphere) is defined as a. The stronger the inversion in the rural air, the greater the value of a. As rural air moves in over the city, it is heated from below in two ways.

1. The release of sensible heat stored in the concrete and asphalt fabric of the city from the solar heating of the previous day.
2. The release of waste heat to the atmosphere as a result of the space heating of homes and commercial buildings, industrial activities, and to a lesser extent automobiles.

Source 1 is stronger in the summer, but in the high latitudes of Canada is almost negligible in winter. Source 2 is small in summer, but is the stronger in mid-winter when its strength is proportional to heating degree-days.

Heating of air, combined with increased mechanical turbulence induced by the buildings, produces a layer of well-mixed air over the city, with a temperature lapse rate between the dry adiabatic and isothermal. As the air moves across the city, more and more heat is added, thus causing a steady increase in the height of the mixed layer. As shown by Summers *(1965)* the following relationships can be developed.

$$T_{CITY} - T_{RURAL} = \left[\frac{2\,HLa}{\rho C_P u}\right]^{1/2} \qquad [1]$$

$$\text{mixing depth } (h) = \left[\frac{2\,HL}{\rho C_P u_a}\right]^{1/2} \qquad [2]$$

in which:

T_{RURAL} = Temperature in the upwind rural area (°C)
T_{CITY} = Temperature in the downtown core (°C)
L = Distance from the edge of the city to the centre along the wind direction (m)
H = Heat input per unit area (cal m^{-2} sec^{-1})

u = Wind speed (m sec^{-1})

ρ = Density of air (gm m^{-3})

C_P = Specific heat of air at constant pressure (cal gm^{-1} per °C)

α = Difference between the upwind temperature profile and the lapse rate over the city (°C m^{-1})

THE POLLUTION MODEL

If the urban area acts as a uniform area source of pollutants that are uniformly mixed in the mixing layer, then the concentration of pollution in the city centre is given by

$$\chi_{CITY} = \frac{QL}{uH} = Q\left[\frac{\rho C_P \alpha L}{2uH}\right]^{1/2} \quad [3]$$

in which:

χ_{CITY} = Pollution concentration in the city (gm m^{-3})

Q = Pollutant input per unit area (gm m^{-2} sec^{-1})

RELATION BETWEEN POLLUTION AND CITY SIZE

For most urban areas that are nearly circular in shape, the population (P) is given by

$$P = \text{const.} \times L^a$$

If the population density is uniform, $a = 2$. However, in most cities the population density is higher close to the centre due to the high density of older buildings, and especially high-rise apartments. Thus $a \geqslant 2$, hence

$$L = \text{const.}\ P^{1/a} \text{ where } a \geqslant 2$$

Substituting in equation 3

$$\chi_{CITY} = \text{const.} \times Q \times \left[\frac{\rho C_P \alpha}{2uH}\right]^{1/2} \times P^{1/2a} \quad a \geqslant 2 \quad [4]$$

The mean annual average of a pollutant is heavily influenced by the large values, which in turn occur under those meteorological conditions favouring poor ventilation (simultaneous low values of u and h; or, alternatively, simultaneous low values of u and high values of α). On a cross-Canada basis,

Table 1.—National air-pollution surveillance network: suspended particulates in commercial downtown core areas vs population for 1971

City	Population	Suspended particulates
	Thousands	$\mu g\ m^{-3}$
Fredericton, N.B.	38	36
St. John, N.B.	107	54
Moncton, N.B.	71	54
Montreal	2,743	132
Ottawa—Hull NCR	602	92
Toronto	2,628	99
Hamilton	499	142
Peterborough	64	61
London	286	125
Sarnia	78	105
Windsor	259	122
Sault Ste Marie	81	55
Thunder Bay	112	69
Winnipeg	540	73
Regina	141	57
Saskatoon	126	72
Edmonton	496	60
Calgary	403	105
Red Deer	28	64
Medicine Hat	29	57
Lethbridge	41	41

Source: Environment Canada (1974).

u is almost constant for Canadian cities, and H tends to be highest where winter inversions are strongest. Thus, a/H does not vary much from city to city; and hence as a first approximation

$$\chi \begin{pmatrix}\text{annual}\\ \text{mean}\end{pmatrix} = \text{const. x } Q \text{ x } P^{1/2a} \quad [5]$$

Apart from a few large industrial sources, particulate emissions in a city are due to a large number of low-level point sources such as home heating units, cars, etc. Assuming that Q is nearly constant from city, then equation 5 reduces to

$$\chi \begin{pmatrix}\text{annual mean}\\ \text{suspended}\\ \text{particulates}\end{pmatrix} = \text{const. } P^{1/2a} \; a \geqslant 2 \quad [6]$$

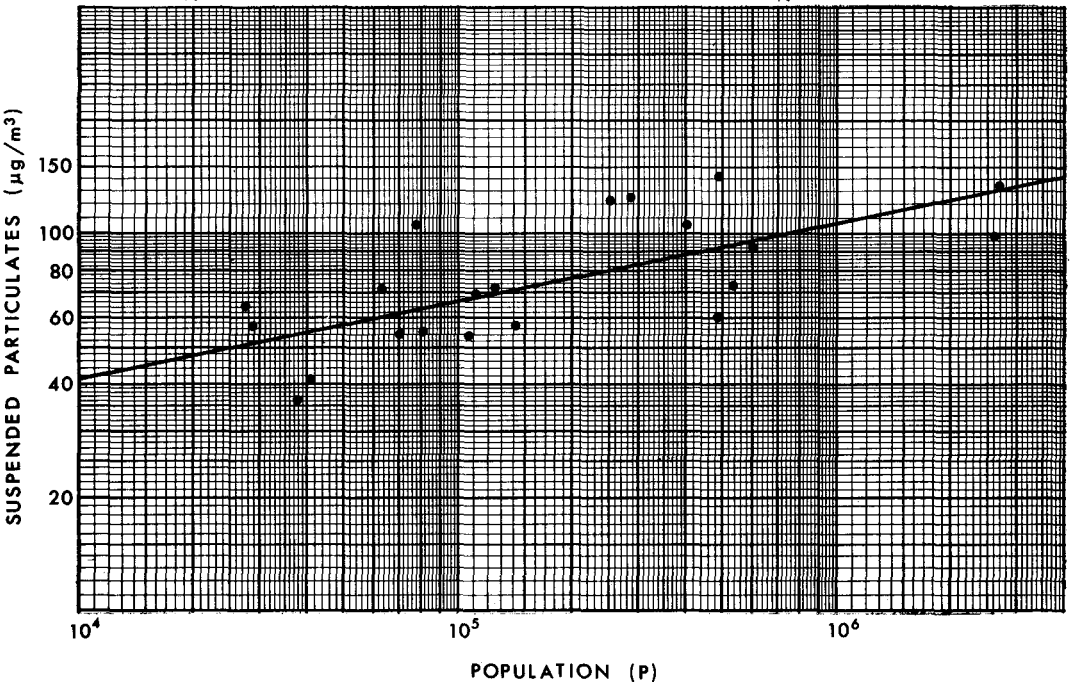
To test equation 6, data from the Canadian Air Pollution Surveillance Network were used (table 1). The population of 21 cities at the time of the last national census in 1971 are listed together with the mean annual suspended particulate levels in the commercial downtown core for the same year *(Environment Canada 1974)*. Note that an effort has been made to locate all these stations in as representative a location as possible away from heavy industry and other large point sources. These data are plotted on log-log paper (fig. 2) and fitted to a power-law curve as shown. The best fit curve is given by

$$\chi = 6.5\ P^{1/5} \quad [7]$$

with a correlation coefficient between χ and P of 0.69.

Note that the data points above the best-fit line correspond mainly to the heavily industralized cities in southern Ontario. Thus there are probably several lines corresponding to different values of Q (see equation 5), all having a slope of approximately 1/5. It also appears that for Canadian cities a = 2.5.

Figure 2.—Relationship between population of Canadian cities and the mean annual downtown suspended particulate levels in 1971. The best-fit power-law curve is $\chi = 6.5\ P^{1/5}$, with a correlation coefficient between χ and P of 0.69.



SOME IMPLICATIONS OF THE MODEL

$$\chi_{CITY} = \text{const.} \times Q \times \left[\frac{a}{uH}\right]^{1/2} P^{1/5} \qquad [8]$$

This simple indicator shows how various factors combine to produce a measure of the downtown air pollution. Some of these (a and u) are meteorological only. One (P) is dependent on city size only. Others (Q and H) are dependent on both city parameters (mainly population density) and meteorological parameters. For example, one of the components of H, and hence Q, is dependent on heating degree-days.

Several important conclusions can be drawn from this indicator of downtown pollution levels:

1. The main controlling factor is the source strength Q (dependent on population density).
2. Meteorological factors, whilst still important, have less controlling effect due to the square-root relationship.
3. Total population is the least important controlling factor because of the fifth-root relationship.
4. A small town with an average value for Q can have a significant value for χ, but once a city is large (population $> 1{,}000{,}000$), then decreasing the rate of growth will have only a minor impact on χ compared to reducing Q.
5. Increasing the heat input H or decreasing the value of Q, with other factors unchanged, reduces χ. Thus the value of switching to cleaner fuels for home heating: coal → oil → natural gas.
6. Energy conservation could possibly increase χ. If a substantial part of Q were not related to heat production and H were cut back, (due to improved home insulation or other conservation measures) at a greater rate than Q^2, then the value of $Q/H^{1/2}$ could increase, resulting in higher values of χ.

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Air Pollution and Urban Climatology at Norfolk, Virginia

by W. MAURICE PRITCHARD *and* KULDIP P. CHOPRA, *Department of Physics and Geophysical Sciences, Old Dominion University, Norfolk, Va. 23508.*

ABSTRACT.—The atmosphere at Norfolk is usually stable, with no strongly prevailing wind direction. Linear regression analyses of visibility data indicate a generally decreasing visibility trend between 1960 and 1972, with a possible trend reversal in later years. A 44 percent increase in the annual frequency of 0-4-mile visibility occurred in 1960-72. Similar analyses of precipitation data for 1960-74 show a slight increase in the annual number of days with precipitation exceeding 0.01 inch. The correlation coefficient between the annual frequencies of low (0-4-mile) visibility and days with precipitation greater than 0.01 inch was rather small and negative.

NORFOLK IS ONE OF FOUR contiguous cities in the Hampton Roads area in the southeastern corner of Virginia. This area is urban and coastal in character, bordering on the Atlantic Ocean. It has no significant concentrations of heavy industry and is generally well ventilated. However, an analysis of weather data for recent years has shown that local variations in certain meteorological parameters may be associated with the effects of particulate air pollutants.

Air pollution influences urban climatologies in a variety of ways. Among these is a decrease in visibility. A low surface visibility due to air pollutants is now a common occurrence in many urban areas. In other areas where air pollution is not a serious problem, decreasing visibility may serve as an indication of an increasing concentration of air pollutants.

The analysis of visibility data is complicated by the fact that visibility is affected by several meteorological factors as well as by air pollutants. The reduction in visibility due to air pollution is almost always associated with particulate matter in the atmosphere. This reduction is due to scattering and absorption of light by airborne particles. Gaseous pollutants are usually either invisible or present in concentrations too low to affect visibility. However, in sufficiently large concentrations, some gases may produce changes in sky color. A high concentration of NO_2, for example, causes a characteristic brownish discoloration of the sky.

As far as precipitation is concerned, particulate air pollutants may furnish additional condensation nuclei. Significant changes in precipitation patterns have been observed at several cities in studies made as a part of Project METROMEX (Metropolitan Meteorological Experiment).

The influence of a particular type of pollutant depends on the size, concentration, and physical properties of the particles. The particle concentration is related to the air volume occupied. This mixing volume can be estimated by using as a vertical dimension the height of the base of a low-lying temperature inversion. Winds serve to dilute the concentration of atmospheric particulate matter by increasing the mixing volume. Low-level atmospheric turbulence also has a diluting effect.

VISIBILITY

In recent years, declining visibility attributed to air pollution has been reported at or near a number of urban areas. These include: Tucson, Arizona *(Green and Battan 1967)*; Point Mugu, California, near Los Angeles *(Lea 1970)*; Los Angeles, *(Chass and Keith 1971)*; Akron, Ohio, Lexington, Kentucky, and Memphis, Tennessee, *(Miller et al. 1972)*; and Norfolk, Virginia, *(Pritchard and Chopra 1972)*. The periods considered were 1949-65 by Green and Battan, 1949-69 by Lea, 1933-69 by Chass and Keith, 1962-69 by Miller et al., and 1960-70 by Pritchard and Chopra. The most pronounced effect observed by all these investigators was a generally increasing trend in the frequency of low visibility. The earlier visibility study by Pritchard and Chopra *(1972)* has now been extended by 4 years and expanded to include consideration of atmospheric stability, wind conditions, and precipitation.

The visibility data analyzed were recorded at the Norfolk Regional Airport in Norfolk, Va. In particular, visibilities measured at noon EST on weekdays were examined for the 15-year period 1960-74. This choice of data is the same as that made by Chass and Keith *(1971)* for the Los Angeles study.

The mean annual visibilities from 1960 to 1972 (fig. 1) show a slight trend toward reduced visibility. The solid line is the linear regression line given by

$$\bar{V} = 8.20 - 0.0275\,N \qquad [1]$$

where V is the mean annual visibility in miles and N = 1, 2, 3, . . . 13 is the year index beginning with N = 1 for 1960. The regression line indicates a slight decreasing trend over the 13-year period. However, a reversal of this trend may have occurred, possibly beginning in 1972. The mean annual visibilities for 1973 and 1974 were 9.17 and 9.57 miles respectively. These values

Figure 1.—Mean annual visibility, 1960-72.

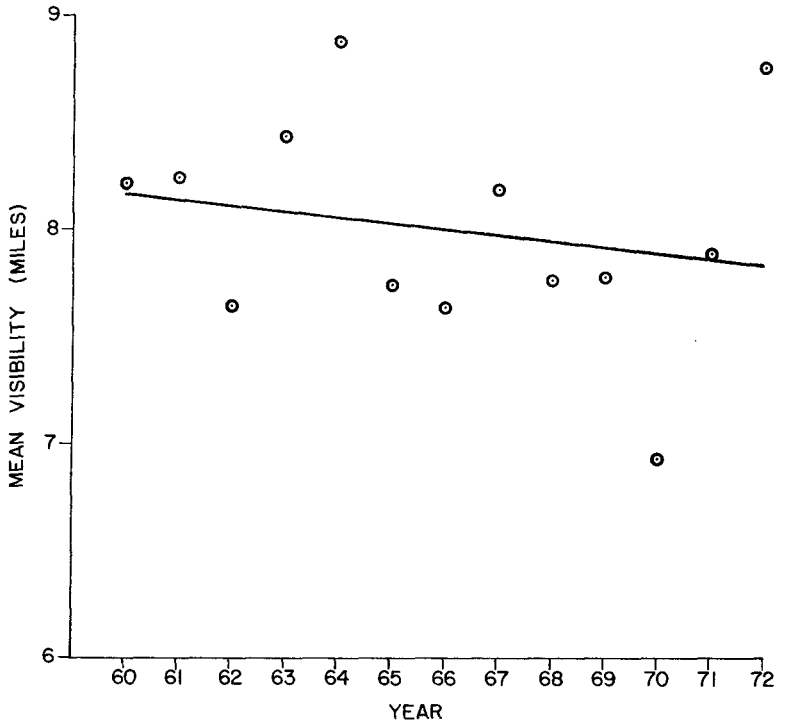


Figure 2.—Annual frequency of 0-4-mile visibility, 1960-72.

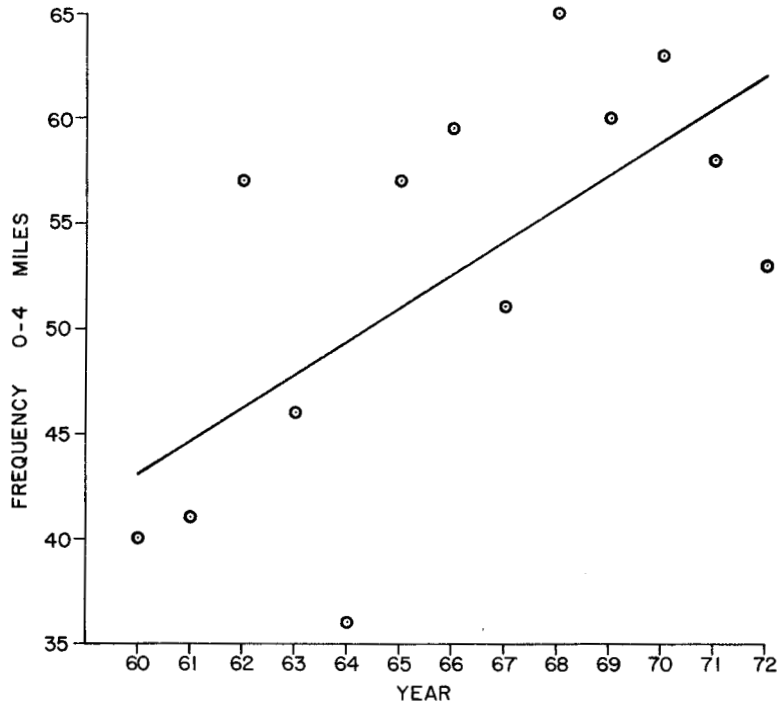
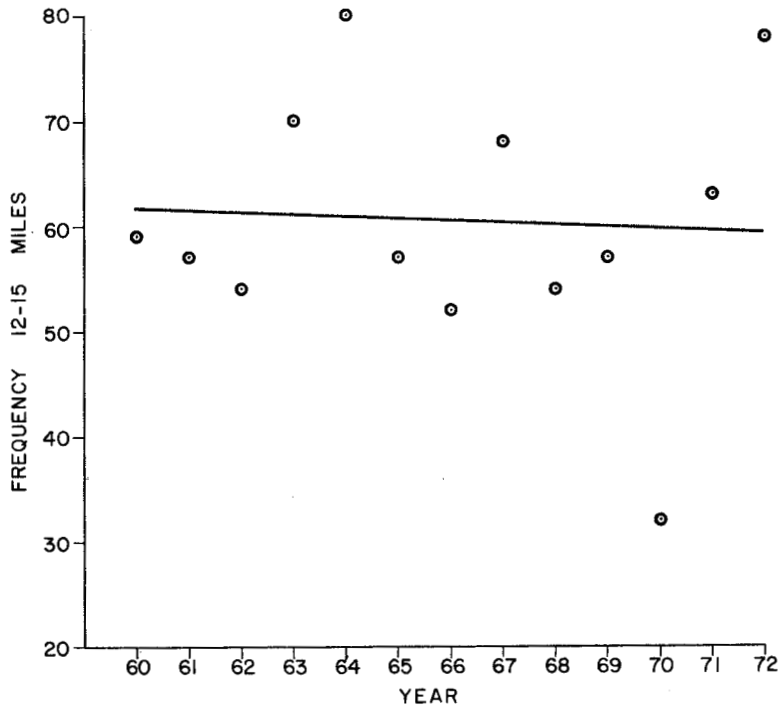


Figure 3.—Annual frequency of 12-15-mile visibility, 1960-72.



are considerably higher than the values given by the regression line.

The annual frequencies of occurrence of visibilities in the 0-4-mile range (fig. 2) for the period 1960-72 fit the regression line

$$F = 41.5 + 1.58\,N \qquad [2]$$

where F is the annual frequency. In this case, a significant increasing trend is observed. The frequence of occurrence of low visibilities, as given by the regression line, increased by 44 percent between 1960 and 1972. A possible trend reversal after 1972 was observed here also. The frequencies of occurrence of visibilities in the 0-4 mile range decreased to 48 in 1973 and to 41 in 1974.

An increase in low visibilities might be expected to indicate a concurrent decrease in high visibilities. The annual frequencies of occurrence of visibilities in the 12-15-mile range (fig. 3) from 1960 to 1972 bear this out. The regression line for these high visibilities is given by

$$F = 61.0 - 0.132\,N \qquad [3]$$

This equation indicates a slight decreasing trend for high visibilities. The data for 1973 and 1974 do not follow this trend. The annual frequencies of occurrence for visibilities in the 12-15-mile range were 102 in 1973 and 205 in 1974. Both of these frequencies are far above the regression line.

PRECIPITATION

The availability of condensation nuclei from anthropogenic sources may lead to increased precipitation patterns in and around urban areas. To investigate this effect, we examined precipitation data from the Norfolk Regional Airport weather station. Data on total annual precipitation, P, (fig. 4) and

Figure 4.—Total annual precipitation, 1960-74.

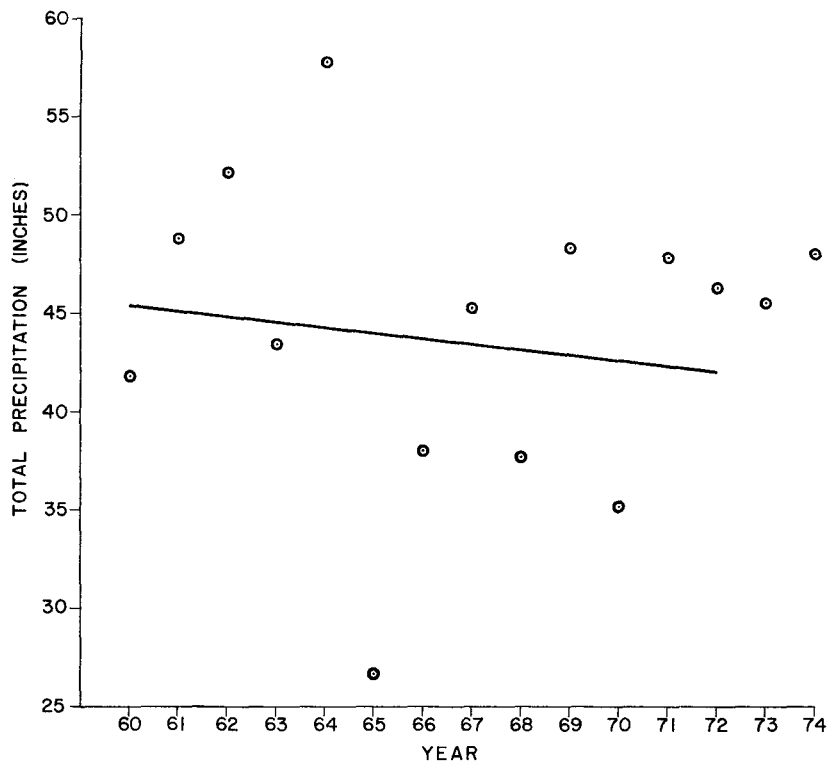
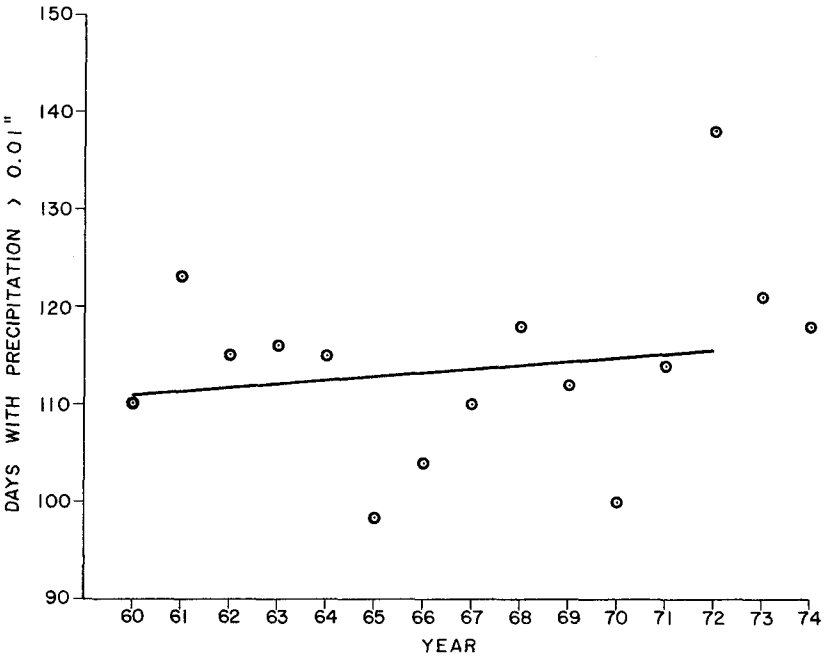


Figure 5.—Annual frequency of days with precipitation greater than 0.01 inch, 1960-74.



annual number of days, F_P, with precipitation greater than 0.01 inch (fig. 5) were considered for the period 1960-74. The regression lines for the data through 1972 are described by

$$P = 45.7 - 0.284\ N \text{ inches} \quad [4]$$

and

$$F_P = 110.7 + 0.379\ N \text{ days} \quad [5]$$

A slight decreasing trend in P and a slight increasing trend in F_P is apparent. The value of F_P computed from the regression equation increased by 4 percent between 1960 and 1974. An examination of the precipitation data (figs. 4 and 5) shows that the data points for 1973 and 1974 follow the trends of the regression lines based on data for the period 1960-72.

AIR FLOW CHARACTERISTICS

The atmospheric flow characteristics of a region have an important bearing on the rate of dispersal of pollutants. These characteristics can be classified as wind speeds and directions and atmospheric stability. The extent of vertical air motion is related to the atmospheric lapse rate, which determines whether vertical motion is enhanced or diminished.

The annual distribution of wind directions (table 1) and frequency of Pasquill stability classes (table 2) were

Table 1.—Annual distribution of wind directions

Wind direction	Distribution
	Percent
N	9.1
NNE	7.1
NE	5.6
ENE	6.6
E	7.1
ESE	3.0
SE	3.9
SSE	5.8
S	9.1
SSW	10.5
SW	6.2
WSW	5.7
W	7.5
WNW	4.0
NW	3.7
NNW	5.1

Table 2.—Annual frequency of Pasquill stability classes

Stability class	Frequency
	Percent
A. Extremely unstable	3
B. Unstable	7
C. Slightly unstable	12
D. Neutral	47
E. Stable	32

determined from data recorded at the Norfolk Naval Air Station between December 1966 and November 1971. The data for this weather station are considered representative of the area, and hourly measurements are made. It appears that, on an annual basis, there is no pronounced prevailing wind direction.

The regional atmosphere at Norfolk displays a generally high stability, which is not usual for an urban area. Normally Pasquill stability class C (slightly unstable) would prevail in an urban environment. This is due to the greater surface roughness and higher temperature environment of cities as compared with rural areas. It is significant that, at Norfolk, stability classes D (neutral) and E (stable) account for 79 percent of all occurrences.

The reasons for the high stability in Norfolk are to some extent geographical. The Norfolk metropolitan area is on a peninsula, and the surrounding water, with low surface roughness, increases the stability of the air passing over it and thus reduces the urban effect. In general, high atmospheric stability is not conducive to the dispersion of air pollutants.

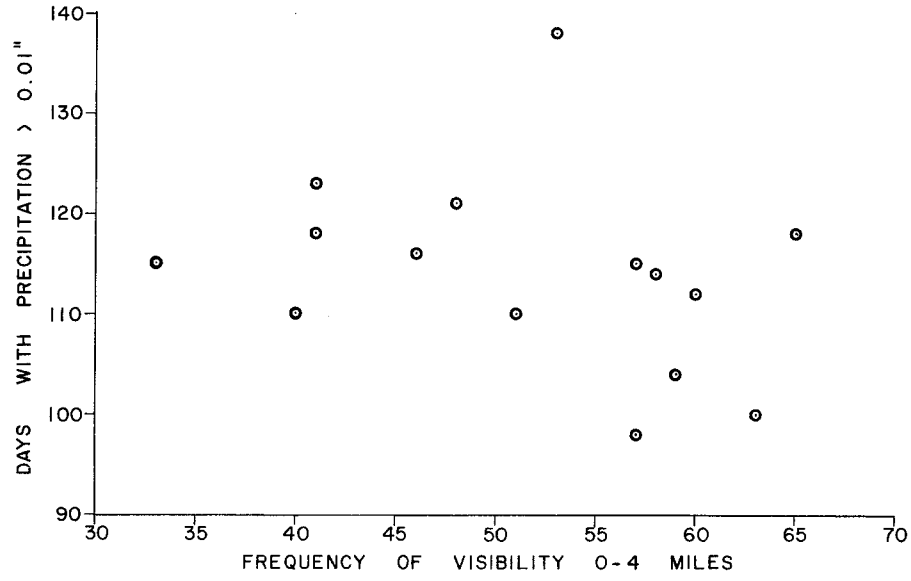
DISCUSSION

A significant decrease in visibility at Norfolk occurred during the 13-year period 1960-72. This decrease may be related to an increasing atmospheric concentration of particulate air pollutants. The most pronounced effect was a substantial increase in the annual frequency of occurrence of low (0-4 mile) visibilities. This result is in agreement with the findings of other investigators for time intervals ending in the late 1960s. For example, Chass and Keith *(1971)* observed that the noon weekday visibility at Los Angeles showed a marked increase in the annual frequency of visibilities in the 3-6-mile range for the 37-year period 1933-69. The declining visibility at Norfolk was associated primarily with sharply lower visibilities during the summer months. This can be attributed to the combined effects of increasing air pollution and a seasonal high in relative humidity. Hygroscopic particles in the atmosphere absorb water and increase in size when the relative humidity is high but the air is unsaturated. Larger particles are more effective in reducing visibility. The same seasonal effect has been observed by Miller et al. *(1972)*.

The extremely high visibilities observed at Norfolk during 1973 and 1974 are somewhat difficult to account for. Some reduction in the generation of particulate air pollutants has occurred. The Virginia Air Pollution Control Board began in 1972 to enforce regulations designed to reduce air pollution from point sources. In the Norfolk Area, the principal point sources of particulate air pollutants were incinerators and businesses engaged in the production of asphalt and fertilizers. Since 1972, particulate emissions from these sources have substantially decreased. However, the extent of the reduction in particulate emissions from heating systems and automobile engines is uncertain.

Precipitation data for the entire 1960-74 period show a slightly increasing trend in the annual frequency of days with precipitation greater than 0.01 inch. This effect may also be due to particulate air pollutants. In addition, some correlation between visibility and precipitation data might be expected. A cross-correlation plot of the annual frequency of days with precipitation ex-

Figure 6.—Correlation between visibility and precipitation, 1960-74.



ceeding 0.01 inch versus the annual frequency of visibility in the 0-4 mile range is shown in figure 6. The correlation coefficient in this case, for the entire 1960-74 period is

$$\rho = \frac{\sum_{i=1}^{15} (F_{vi} - \bar{F}_v)\,(F_{Pi} - \bar{F}_P)}{\left[\sum_{i=1}^{15} (F_{vi} - \bar{F}_v)^2 \sum_{i=1}^{15} (F_{Pi} - \bar{F}_P)^2\right]^{1/2}} = -0.296 \qquad [6]$$

Here F_{vi} and F_{Pi} are the annual frequencies for visibility and precipitation respectively, and $\bar{F}_v$ and $\bar{F}_P$ are the 15-year averages of the F_{vi} and F_{Pi} values. The correlation coefficient, although rather small, is negative and is consistent with the hypothesis that the effect of precipitation is to increase visibility by washing particulate matter out of the atmosphere.

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Development of Alternative Sulfur Dioxide Control Strategies for a Metropolitan Area and its Environs, Utilizing a Modified Climatological Dispersion Model

by K. J. SKIPKA *and* D. B. SMITH, *senior environmental meteorologist and director of meteorology, Equitable Environmental Health, Inc., 333 Crossways Park Drive, Woodbury, N. Y. 11797.*

ABSTRACT.—Alternative control strategies were developed for achieving compliance with ambient air quality standards in Portland, Maine, and its environs, using a modified climatological dispersion model (CDM) and manipulating the sulfur content of the fuel oil consumed in four concentric zones. Strategies were evaluated for their impact on ambient air quality, economics, and fuel oil resources. Based on these evaluations, a control strategy best suited for meeting the needs of the Portland area could be recommended.

IMPLEMENTATION PLANS for meeting ambient air quality standards were prepared by most states in the early 1970s pursuant to requirements of the Clean Air Act of 1970. These plans mandated various measures for controlling pollutant emissions to ensure compliance with the standards. However, implementation of the control strategies met with varying degrees of success.

Prompted by the failures, reevaluations of control strategies in the past year have highlighted a number of questionable approaches in strategy development. For example, a major shortcoming in the development of many strategies was the assumption that all pollutant sources should be controlled by the same percentage amount to achieve improved air quality. This approach to strategy development was commonly called the "rollback" procedure.

The rollback procedure was the basis for establishing in 1972 the control strategy *(Maine Dep. Environ. Protect. 1972)* for sulfur dioxide emissions in the Metropolitan Portland Air Quality Control Region (AQCR). The Portland AQCR encompasses Cumberland, Sagadahoc, and York Counties and a small portion of Oxford County in southern Maine (fig. 1). A substantial body of air quality data has been collected in the region in the past several years by the State Department of Environmental Protection and industrial concerns. All monitoring data indicate that ambient sulfur dioxide concentrations throughout the AQCR are well below the federal EPA standards except in the downtown area of Portland. There, violations of federal and state 24-hour average and annual average standards have been and continue to be recorded. Measured 24-hour average sulfur dioxide concentrations at one location in the downtown Portland peninsula have exceeded the state standard by 100 percent, and measured annual average levels have exceeded the standard by 50 percent.

Recent examinations of air quality data collected in the Portland AQCR since 1972 indicated that the originally developed rollback strategy would be ineffective in solving regional air quality problems. Realizing that there were several alternatives for solving the re-

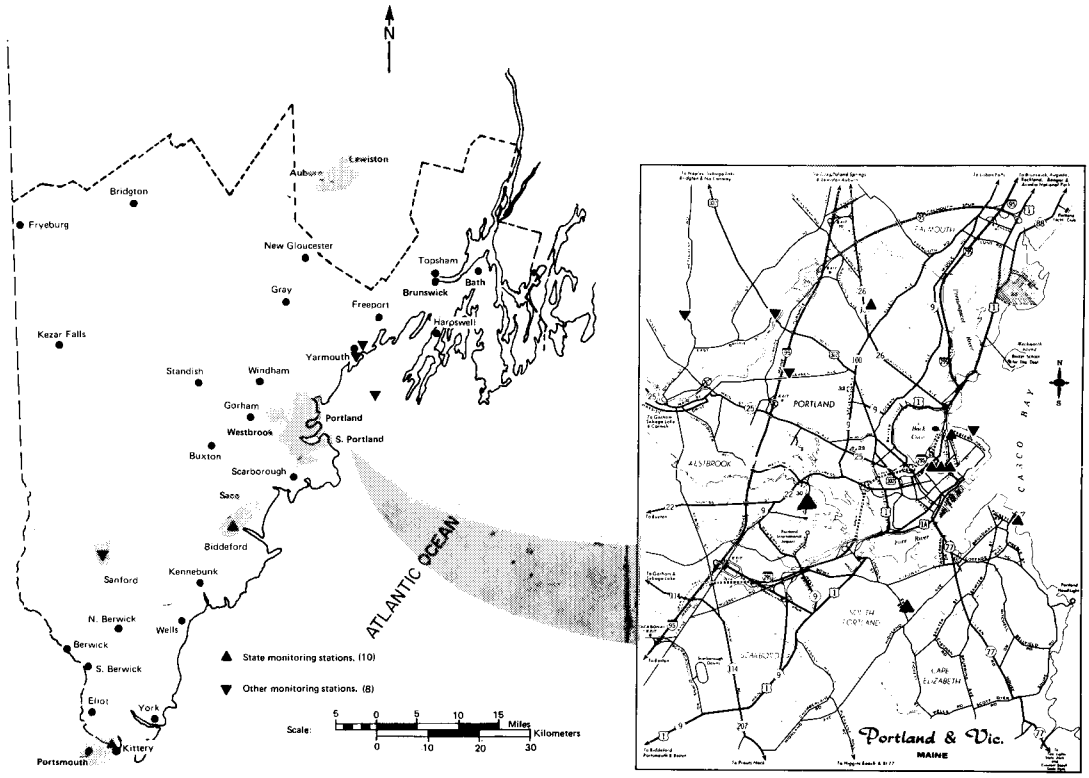


Figure 1.—The Maine Metropolitan Portland Air Quality Control Region.

gional problem, the Maine Board of Environmental Protection heard evidence on alternative control strategies from the Maine Department of Environmental Protection and all other interested individuals. These opinions and suggestions were presented before the Board at a public hearing on 16 April 1975. The thorough reevaluation and development of the Portland sulfur dioxide control strategy, which is described in this paper, was presented at that time.

REGIONAL AIR QUALITY MODEL AND MODEL VALIDATION

The Climatological Dispersion Model (CDM) developed by the federal Environmental Protection Agency *(Calder 1973, Busse and Zimmerman 1973)* was the principal tool used to evaluate both the regional air quality problem and, subsequently, alternative solutions. The CDM is a computer code that uses input data on pollutant concentrations based on generally accepted principles.

CDM's emission inventory input capability was expanded to accommodate different categories of fuel use for both point and area sources and for different geographical areas. The purpose of this modification was to permit testing of the effect on ambient air quality of variation in the sulfur level in fuel oil both as a function of fuel type (No. 6, No. 4, and No. 2) and as a function of geographical area (downtown and suburbs).

To use CDM in the Portland AQCR, the model had to be validated for application to both 24-hour and annual time periods. This important first step

was accomplished by assembling an extensive data base comprised of ambient sulfur dioxide concentration measurements, meteorological observations, and a sulfur dioxide emission inventory.

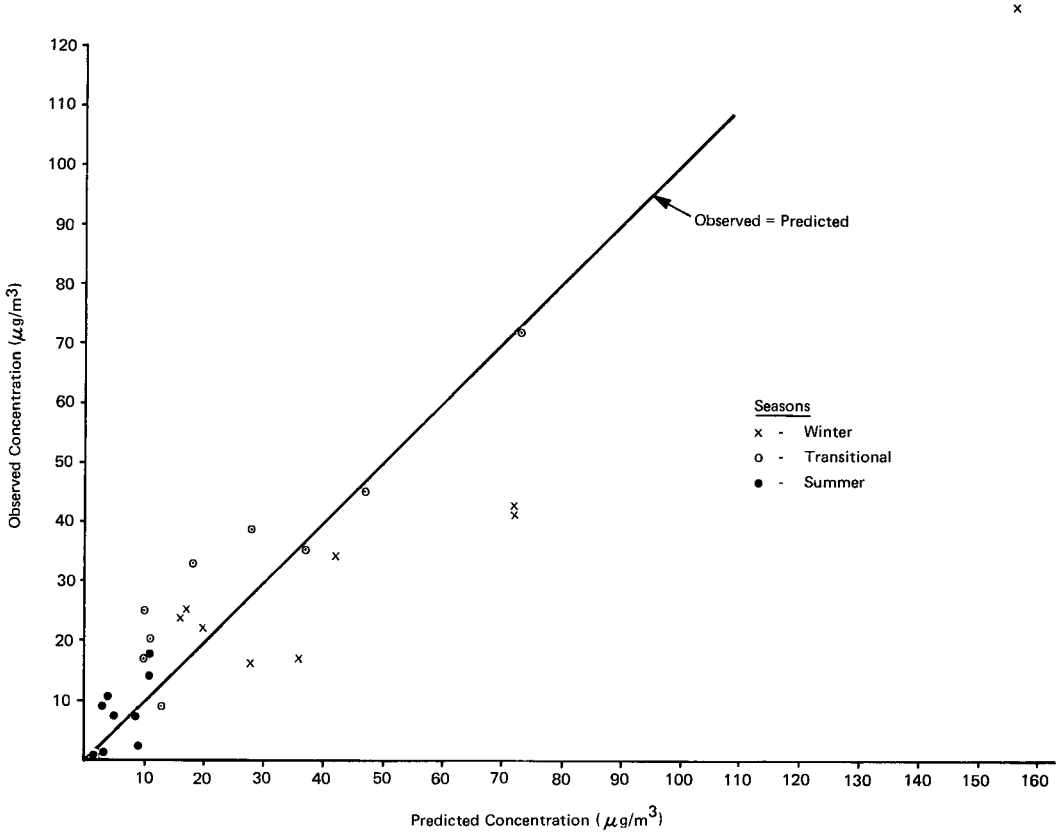
The year October 1973 through September 1974 was selected for validating CDM over an annual period because the most comprehensive set of sulfur dioxide measurements were available for this period. This data set included continuous measurements at two downtown sites and two suburban sites and measurements on an every-sixth-day schedule at seven additional sites in the AQCR. Meteorological data were assembled from the National Weather Service station at the Portland International Jetport.

A total of 8 days in 1973 were selected for validating CDM for application to 24-hour periods. The days selected include 5 on which the sulfur dioxide concentration measured in downtown Portland was the highest recorded at street level in the Portland AQCR.

CDM was successfully validated for both 24-hour and annual periods for the Portland AQCR based on comparisons of calculated and observed concentrations. The correlation coefficient for calculated and observed concentrations at the monitor location of maximum concentration, the Masonic Building in downtown Portland, was 0.78 for 24-hour periods. The correlation for all monitoring locations in the AQCR was 0.67 for 24-hour periods.

The correlation coefficient for all calculated and observed annual average concentrations in the AQCR was 0.96. These annual averages were calculated by taking the mean of three seasonal averages (fig. 2). Seasonal averages were

Figure 2.—Seasonal predicted versus observed sulfur dioxide concentrations in the Portland AQCR, 1973-74.



calculated because of the large variability, typically an order of magnitude, in ambient sulfur dioxide levels from winter to summer. Generally, CDM-predicted concentrations were higher than observed concentrations for both 24-hour and annual periods.

AIR QUALITY PROJECTIONS

Numerous violations of the 24-hour standard and several violations of the annual ambient air quality standard for sulfur dioxide have been recorded in downtown Portland. If no controls are placed on sulfur dioxide emissions, it is reasonable to assume that such violations will recur. These recurrences will probably increase in severity and frequency because of the additional sulfur dioxide emissions that accompany population growth. Hence, any plan designed to resolve the existing problem must also account for worsening of the problem due to such growth. Furthermore, the federal EPA requires that control strategies account for projected growth in an AQCR over the next decade.

Growth is not the only factor that must be considered in designing a control strategy. Meteorological conditions vary from day to day and from year to year. Because the Maine standards allow for no 24-hour average or annual average concentration of sulfur dioxide above the standard, it is only prudent to account for the most adverse meteorological conditions that might be expected over a 24-hour and annual period during the coming decade.

Projections to the data base were made to account for both increased sulfur dioxide emissions due to population growth and the most adverse meteorological conditions. Projected growth in the AQCR was accounted for through 1985 by proportionally increasing the area source emission inventory. Additionally, all emissions were increased to account for increased heating requirements due to very cold weather. Finally, the most adverse meteorological conditions that might be expected over the next 10-year period were projected. The projected emission inventory and meteorological conditions were then combined in CDM to calculate the worst probable air quality levels through the year 1985.

The projected maximum sulfur dioxide concentrations for 24-hour and annual periods consistently fell below the standards except in the downtown Portland peninsula. There, maximum levels projected by CDM exceeded the standards by larger margins than had recorded maximum levels. The projected peak 24-hour average sulfur dioxide concentration is 550 micrograms per cubic meter at the Masonic Building, with projected peak levels above the standard of 230 micrograms per cubic meter over most of the downtown Portland peninsula (fig. 3 and 4). The projected peak annual average is 97 micrograms per cubic meter, again at the Masonic Building, with projected peak levels above the standard of 57 micrograms per cubic meter in the center of the peninsula (table 1).

DEVELOPMENT AND EVALUATION OF ALTERNATIVE CONTROL STRATEGIES

The air quality projections essentially defined the extent and magnitude of the sulfur dioxide air quality problem in the AQCR through 1985. Using CDM as a tool, alternative strategies for solving the problem were developed and evaluated. In addition, an assessment of the impact of these strategies on fuel costs was included in the evaluation.

Following the approach to the problem of the rollback strategy, an average fuel sulfur content limit required throughout the AQCR to meet state standards could be determined using CDM. However, in this study, the approach taken was to examine the problem and develop solutions specifically tailored to the problem.

Violations of the 24-hour and annual

Figure 3.—Predicted peak 24-hour concentrations, northwest wind. (Concentration in $\mu g/m^3$.)

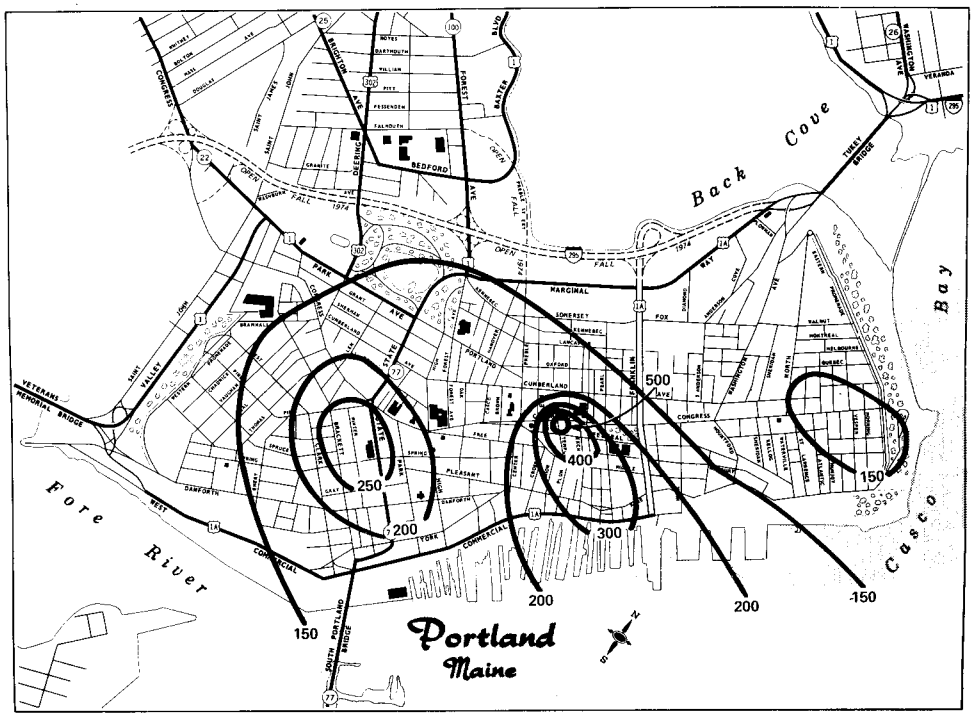


Figure 4.—Predicted peak 24-hour concentrations, southwest wind. (Concentration in $\mu g/m^3$.)

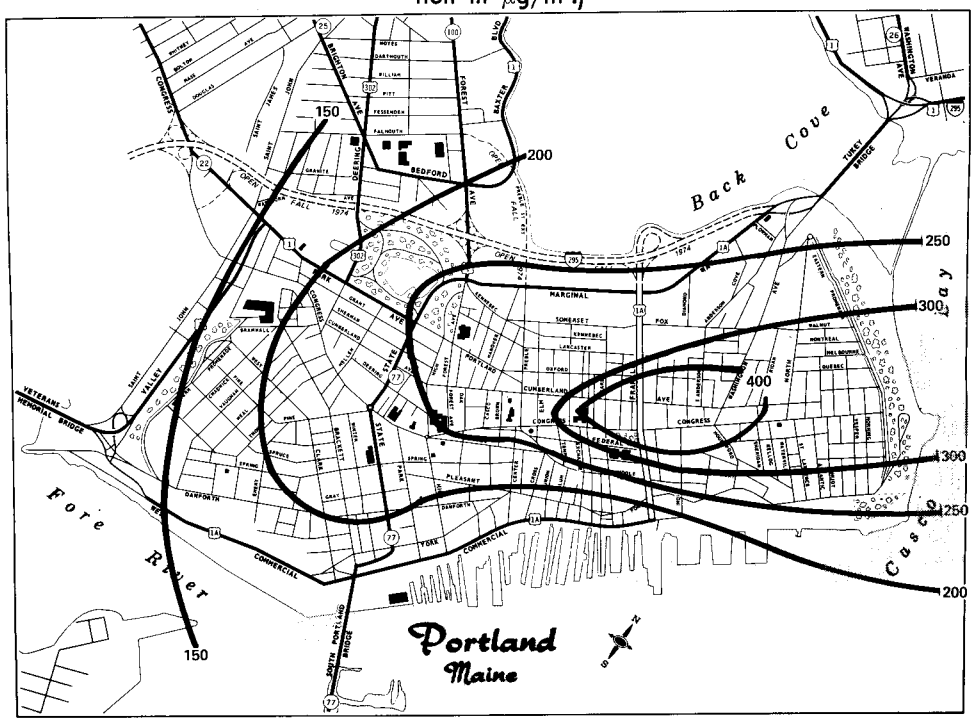


Table 1.—Average fuel sulfur contents required to achieve compliance with state standards for each alternative control strategy

Alternative control strategy	Area of fuel sulfur content control	Average sulfur content		
		No. 6 fuel	No. 4 fuel	No. 2 fuel
24-hour compliance:		*Pct.*	*Pct.*	*Pct.*
A	Downtown Portland Peninsula	0.7	0.7	0.25
B	Portland and South Portland	.8	.8	.25
C	Portland SMSA	.9	.9	.25
D	Entire Portland AQCR	.9	.9	.25
Annual compliance:				
A	Downtown Portland Peninsula	.9	.9	.25
B	Portland and South Portland	1.0	1.0	.25
C	Portland SMSA	1.1	1.1	.25
D	Entire Portland AQCR	1.1	1.1	.25

sulfur dioxide standards were projected in the downtown Portland peninsula only. The highest 24-hour average levels were projected for areas along Congress Street in the center of the downtown peninsula. The major contributors to this problem were identified by the CDM as the users of residual oil in the downtown peninsula. Because the problem was geographically isolated, control strategies for fuel oil sulfur content were developed with a major focus on geography.

Four alternative strategies to bring sulfur dioxide levels in the downtown area into compliance with air quality standards were formulated. These strategies consisted of controlling sulfur dioxide emissions only within specific geographical areas by selectively reducing the average sulfur contents of heavy fuels within these areas alone.

The four alternative strategies differed only in respect to the geographical area within which the controls were exerted. The four geographical areas within which fuel sulfur level controls were exerted are listed below:

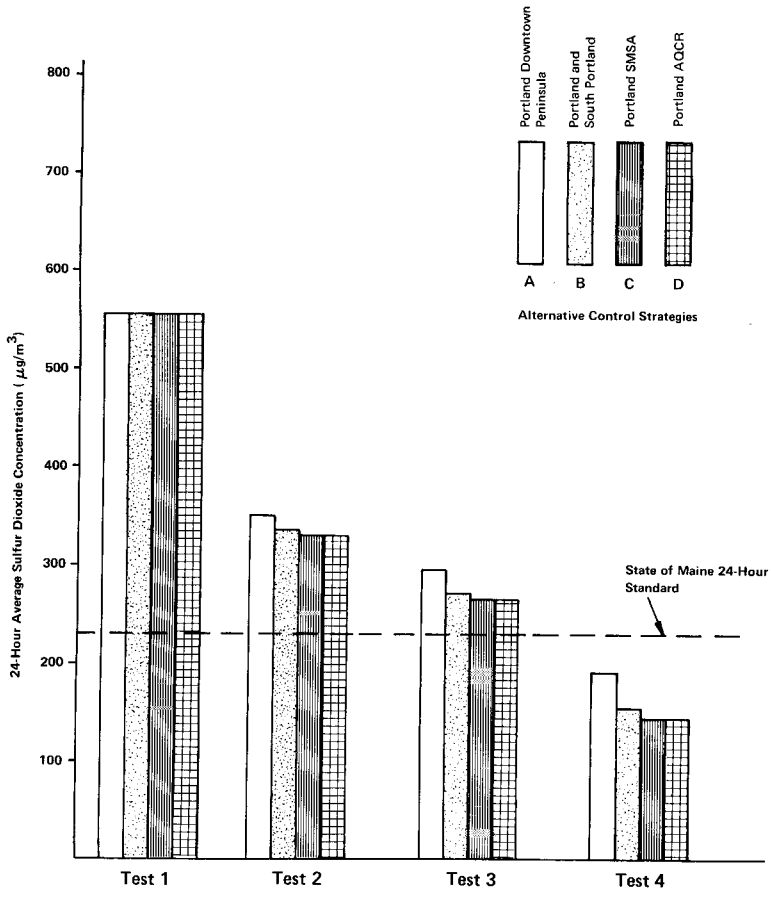
1. Alternative A—Controls on fuel sulfur content within the downtown peninsula only of the city of Portland (the dividing line between the mainland and the peninsula was taken as Interstate 295).
2. Alternative B—Controls on fuel sulfur content within the cities of Portland and South Portland only.
3. Alternative C—Controls on fuel sulfur content within the metropolitan Portland area only (defined as the U. S. Census Bureau's Portland Standard Metropolitan Statistical Area, which includes Portland, South Portland, Cape Elizabeth, Scarborough, Westbrook, Gorham, Cumberland, Falmouth, and Yarmouth).
4. Alternative D—Controls on fuel sulfur content within the entire Portland AQCR.

The CDM predictions showed convincingly that the current average sulfur contents of heavy fuels must be reduced to meet ambient air quality standards. To determine the average sulfur contents of heavy fuels required to meet the standards for each alternative strategy, a series of CDM tests were run. Progressively lower average sulfur contents of No. 6 and 4 fuel were used in each successive test, as defined below, with No. 2 fuel at an average sulfur content of 0.25 percent in all cases.

Test 1—Existing average sulfur contents of heavy fuel oils, with No. 6 at an average of 2.3 percent and No. 4 at an average of 1.27 percent.

Test 2—No. 6 fuel average sulfur content reduced to that of No. 4 fuel, with both No. 6 and No. 4 at an average of 1.27 percent.

Figure 5.—The 24-hour test sequence for the locus of maximum predicted concentration at the Masonic Building monitor.



Test 3—No. 6 and 4 fuel average sulfur content reduced, with both No. 6 and No. 4 at an average of 1.0 percent.

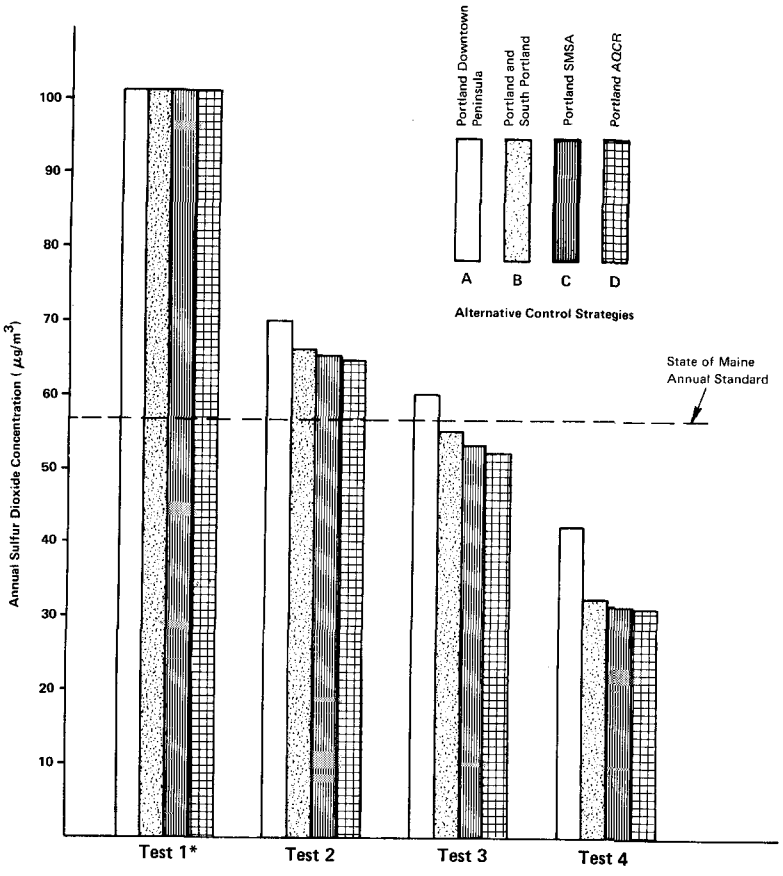
Test 4—No. 6 and 4 fuel average sulfur content further reduced with both No. 6 and No. 4 at an average of 0.5 percent.

Test 1, of course, represents worst-case projections without controls. Projected ground-level concentrations at the location of maximum concentration in the Portland AQCR, which is at the Masonic Building monitor, were shown for the 24-hour period and for the annual period. These concentrations represent the magnitude of peak sulfur dioxide concentrations under projected worst-case meteorological and emission-rate conditions. Both projections show that ambient concentrations would exceed state standards by a considerable margin.

In test 2, the average sulfur content of No. 6 fuel was reduced from 2.3 to 1.27 percent, the same average sulfur content as No. 4 fuel. The predicted ground-level concentrations for test 2 still exceeded state standards for both the 24-hour (fig. 5) and annual (fig. 6) time frames for all alternative strategies.

Predicted concentrations for the 24-hour case of test 3 continue to exceed the state standards for all alternative strategies. However, for the annual case the standard is exceeded only with al-

Figure 6.—Predicted annual sulfur dioxide concentration for alternative control strategies, Masonic Building monitor.



ternative A. The remaining alternative strategies bring levels below the standard and are acceptable strategies for assuring compliance with the state sulfur dioxide annual standards.

As anticipated, achieving compliance with the 24-hour standard requires a more restrictive fuel sulfur content than required to achieve compliance with the annual standard. Although compliance with the annual standard may be possible at the test 3 sulfur content level with alternative A, the same sulfur combination in fuel oils will not meet the 24-hour state standard (see comparisons, figures 5 and 6).

The average fuel sulfur contents that would assure compliance with the 24-hour standard and the annual standard were derived by interpolation between test 3 and test 4 (table 2). The average fuel sulfur contents for the 24-hour compliance case are more restrictive than for the annual case. To assure compliance with both 24-hour and annual standards, a set of alternatives that establishes compliance with the 24-hour standard must be selected.

In order to place into perspective the cost of implementing each strategy, a brief economic analysis was prepared. Generally, the economic impact of implementing a given control strategy will depend on the number of affected fuel oil users, the affected volume of oil consumption, and the reduction in fuel sulfur content required. The economic analysis prepared here accounts only

Table 2.—Predicted peak annual concentrations at monitoring sites

Site	Annual concentration
	$\mu g/m^3$
Jack Junior High School	46
Lyseth School	12
Portland Jetport	15
South Portland High School	25
South Maine Vocational Training Institute	35
Portland High School	72
Masonic Building	97
Mobile Van (Downtown Location)	66
Stroudwater (S.D. Warren)	22
Warren Avenue (S.D. Warren)	13

for the differential cost between fuel of the current and required sulfur contents.

This economic analysis does not account for the expenses that might be incurred if changes to the present boiler configurations are required. Nor does it include any of the other expenses that might be required as a result of implementing the proposed alternative control strategies. The analysis also assumes that sufficient oil of the required sulfur content will be available for fulfilling the needs of the selected strategy.

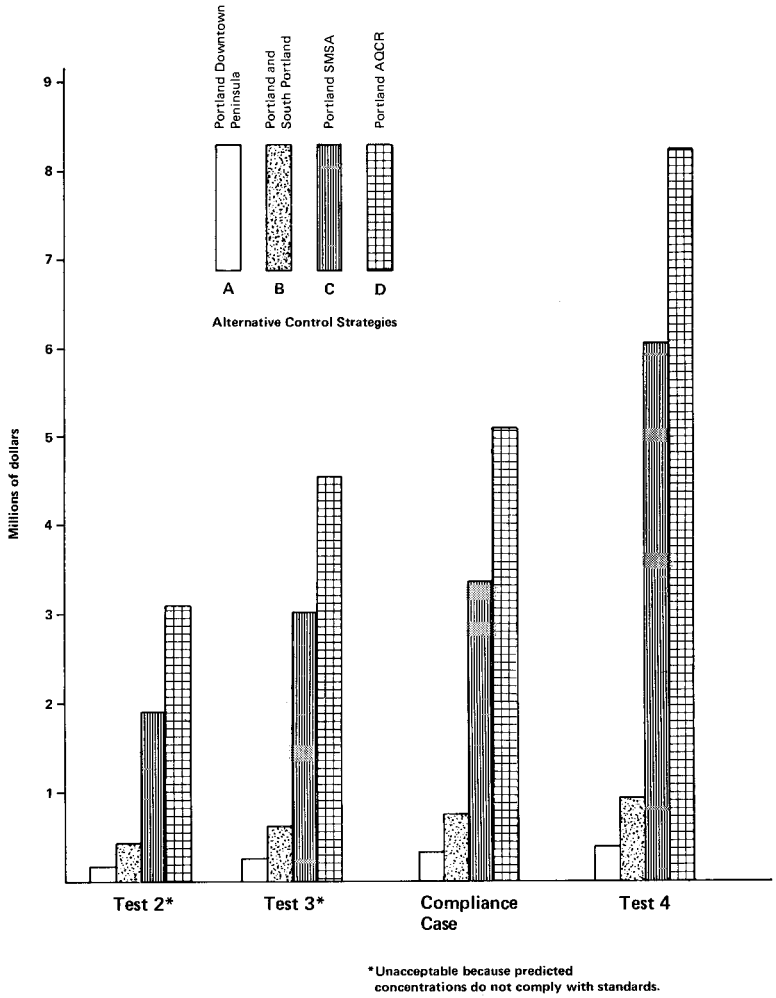
The 24-hour test case was shown to be the limiting case in terms of compliance with state standards. The economic analysis was therefore established for the average sulfur content of fuel oil specified by the 24-hour case. The annual case was not considered because less stringent reductions in fuel sulfur content were required for assuring compliance with state standards.

The results of the economic analysis per test case and alternative strategy show that costs increase dramatically as fuel sulfur level decreases and the area of control or volume of fuel affected increases (fig. 7). Test 1 is not included because it represents the status quo and no expenditures would be required. Tests 2 and 3 show costs increasing as fuel users in the Portland AQCR are subjected to increasingly stringent controls on fuel sulfur content. However, these tests are unacceptable in terms of meeting state sulfur dioxide standards. Test 4 was shown to be overrestrictive in regulating the fuel sulfur content in meeting ambient-air quality standards.

The compliance case, intermediate to tests 3 and 4, restricts fuel sulfur content only to the degree required to achieve compliance with the state standard. A comparison of the incremental costs for implementing each of the four alternatives in the compliance case shows that alternative A is the least expensive. The total incremental annual cost for implementing this strategy would be an estimated $330,000.

The results of this study and their analyses were presented at a hearing before the Maine Board of Environmental Protection. Subsequent to the hearing, the Board promulgated a new strategy for meeting sulfur dioxide ambient air quality standards in the Portland AQCR. The Board established a subregion within the original Metropolitan Portland AQCR, denoted as the Portland Peninsula Air Quality Control Region. Included in this subregion are all monitoring locations where violations had occurred. The fuel used in the subregion after 1 November 1975 was restricted to a maximum sulfur content of 1.5 percent, and the remainder of the Metropolitan Portland AQCR was per-

Figure 7.—Incremental annual costs associated with 24-hour test sequences for alternative control strategies.



mitted to use fuel with a sulfur content not exceeding 2.5 percent. The action of the Board indicates a consideration of several alternative strategies, and the final selection was based on economics and fuel supplies as well as assuring compliance with standards.

Acknowledgments. The authors acknowledge the support of the S. D. Warren Division of Scott Paper Company, the Central Maine Power Company, and the Bath Iron Works Corporation in funding this study.

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Fugitive Dust from Vehicles Travelling on Unpaved Roads

by THOMAS A. CUSCINO, ROBERT JENNINGS HEINSOHN, *and* CLOTWORTHY BIRNIE, JR., *respectively research assistant, Center for Air Environment Studies; associate professor of mechanical engineering, Center for Air Environment Studies; and associate professor of mechanical engineering, The Pennsylvania State University, University Park, Pa.*

ABSTRACT.—A model has been developed for estimating concentrations of fugitive dust downwind of an unpaved road within a factor of 2 for most cases. The model allows for winds oblique to the road and also for extraction of fugitive dust from the plume as it diffuses to the ground. Experiments were performed to determine the accuracy of the model in estimating downwind concentrations of fugitive dust generated by a vehicle travelling on a gravel road.

AN OFTEN NEGLECTED factor that contributes to the inadequacy of a region's air is fugitive dust. Fugitive dust is defined as any solid particulate matter that does not come from a stack or flue. It contributes to particulate concentrations in several Air Quality Control Regions that still exceed the National Ambient Air Quality Primary and Secondary Standards *(Environmental Protection Agency 1974)*.

There are several sources of fugitive dust in the urban environment:

1. Unpaved surfaces of travel; for example, roads, private driveways, and parking areas.
2. Paved roads, which yield a fine dust as their surfaces wear.
3. Building construction and demolition.
4. Highway construction and repair.
5. Tire and brake-lining wear.

By far the most significant contributor of fugitive dust to the total suspended particulate burden is vehicular travel on paved and unpaved surfaces. This paper is concerned solely with the prediction of fugitive dust concentrations downwind from unpaved roads, although the principles are applicable also to paved roads.

THE PREDICTIVE MODEL

As a vehicle travels over an unpaved surface, dust is elevated by two mechanisms. First, dust adheres to the tire as the tire rolls over the unpaved surface; the dust is then detached from the tire by centrifugal force and entrained in the turbulent wake of the vehicle. Second, turbulent eddies created by the passage of the vehicle sweep the fine dust from the ground and mix it upward. Both of these mechanisms cause the vehicle-road interaction to be a source of fugitive dust.

To develop an easy-to-use predictive scheme for estimating concentrations with reasonable accuracy, this source has been theoretically modeled as an elevated continuous line source of infinite extent. The assumptions inherent in this model are:

1. The particles distribute themselves in a Gaussian fashion in the vertical direction.
2. The fugitive dust is small enough that it moves exactly as the air.
3. The unpaved road is heavily travelled so that the generation of dust by traffic can be treated as a source that does not vary with time.

4. The wind speed and direction are not a function of height above the ground.
5. The car velocity greatly exceeds the wind velocity so that a line source essentially parallel to the road is generated.
6. The distance from the road at which concentrations are predicted is sufficiently small in comparison to the length of the road so that the road can be modeled as a line source of infinite length and end effects can be neglected.
7. The airborne fugitive dust particle-size distribution is such that it can be represented as a monodispersoid.

Fugitive road dust can be injected into the atmosphere continuously or instantaneously. A single vehicle travelling on a road at a speed much greater than the wind speed can be viewed as an instantaneous line source. On the other hand, many closely spaced cars travelling over the road can be modeled as a continuous line source.

Because the road dust is first of all mixed upward by the vortices trailing behind the moving vehicle, the vehicle-road interaction can be modeled as an elevated continuous line source. The turbulent wake region can be modeled as a volume of constant concentration called the mechanical mixing cell *(Beaton et al. 1972)*. Beaton references work by Eschenroder as the basis for the statement that the height of the mixing cell is approximately twice the height of the vehicle. The width of the cell is assumed to be the shouder-to-shoulder distance across the road, provided this distance is less than 30 feet. In an effort to develop a simplified model, the mixing cell, which is actually a volume source of dust, is modeled as a line source elevated to the height of the volume source and located above the center line of the road.

The conventional equation *(Turner 1970)* for describing the concentration downwind from a continuous line source of infinite extent emitting a dust plume that expands in a semi-infinite medium is

$$c = \frac{Q_T}{u \cdot \sin\theta \cdot \sqrt{2\pi} \cdot \sigma_z(x)} \left\{ \exp\left(-\tfrac{1}{2}\left(\frac{z-h}{\sigma_z(x)}\right)^2\right) + \exp\left(-\tfrac{1}{2}\left(\frac{z+h}{\sigma_z(x)}\right)^2\right) \right\} \quad [1]$$

where

c = Concentration (g/m^3)
u = Mean wind speed (m/s)
Q_T = Total line source strength as measured at the road (g/m-sec)
θ = Angle between the wind vector and the road (degrees)
σ_z = Vertical dispersion parameter (m)
z = Height above ground (m)
x = Distance downwind of the source (m)
h = Height of the source above ground (m) $= 2 \cdot V_H$ (m)
V_H = Vehicle height (m)

This model is designed to allow for diffusion in an oblique wind and to neglect particulate settling (assumption 2).

Equation 1 can be further refined by allowing the ground to adsorb any particulate matter that diffuses to the surface. A model was proposed *(Johnstone 1949)* that postulated an infinitely thin layer at the earth's surface into which particles that diffused would be adsorbed. The adsorption process was modeled as a function of the Stokes terminal velocity of the particle, which is calculated by equating the drag and gravitational forces on the particle. To allow for this subtraction of particulate matter from the plume, an image source was postulated that emits less particulate than the image in equation 1. This was achieved by placing a deposition coefficient (a) before the image term as follows:

$$c = \frac{Q_T}{u \cdot \sin\theta \cdot \sqrt{2\pi} \cdot \sigma_z(x)} \left\{ \exp\left(-\tfrac{1}{2}\left(\frac{z-h}{\sigma_z(x)}\right)^2\right) + a \cdot \exp\left(-\tfrac{1}{2}\left(\frac{z+h}{\sigma_z(x)}\right)^2\right) \right\} \quad [2]$$

Equation 2 contains two unknowns, a and c; and thus another relationship is needed. Johnstone postulated that the second relationship should be the continuity equation

$$Q_T = {}_0\int^x V_s \cdot c\,(x',0)\,dx' + {}_0\int^\infty \bar{u}_\perp \cdot c\,(x',z)\,dz \quad [3]$$

where

$u_\perp$ = The mean wind perpendicular to the road (m/sec)

x' = A dummy variable representing downwind distance (m)

V_s = The particle terminal velocity as determined by the Stokes equation (m/sec)

Equation 3 states that the total mass emitted from the source equals that which has diffused to the surface up to a distance x plus that which passes through a semi-infinite plane beginning at the ground and at a distance x downwind from the road.

Four factors must be known to solve equations 2 and 3 simultaneously. First, the mean wind speed and direction must be known at the site of the unpaved road. This must be obtained either by measurement or by review of climatological data. Second, the source strength must be known. The source strength can be defined as follows:

$$Q_T = E_T \times f \quad [4]$$

where

E_T = Total emission factor measured at the road (g/vehicle-meter)

f = Frequency of vehicle passage (vehicle/sec)

A useful estimate of the total emission factor has been obtained *(Roberts 1973)* for speeds from 10 to 30 mph on paved and unpaved surfaces (table 1). Third, the vertical dispersion must be acquired. The Pasquill-Gifford curves *(Turner 1970)* can be utilized for this purpose. Finally, the particle fall velocity must be attained. From measurements we have made, distributions of fugitive dust from gravel roads (density of limestone = 2.7 g/cc) have yielded an average number geometric mean diameter for fugitive dust of 1.6 micrometers, with an average standard deviation of 2.9. Representing the polydisperse aerosol as a monodispersoid with a diameter of 1.6 micrometers, the Stokes fall velocity can be calculated.

Table 1.—Emission factors for fugitive dust from vehicle-road interactions (Roberts 1973)

Vehicle speed (mph)	Type of road	LBS/VM* total particulate	LBS/VM below 10 microns	LBS/VM below 2 microns
10	Gravel road	3.5	0.58	0.10
20	Gravel road	7.0	1.9	.24
30	Gravel road	22.2	9.0	.77
20	Dusty paved road, no curbs	.83	.17	.022
20	Paved road with curbs, flushed weekly swept biweekly	.14	.0055	—

*LBS/VM=pounds mass per vehicle mile.

Figure 1.—A comparison of the theoretical versus experimental results on 6 August at 18.3 m from the road.

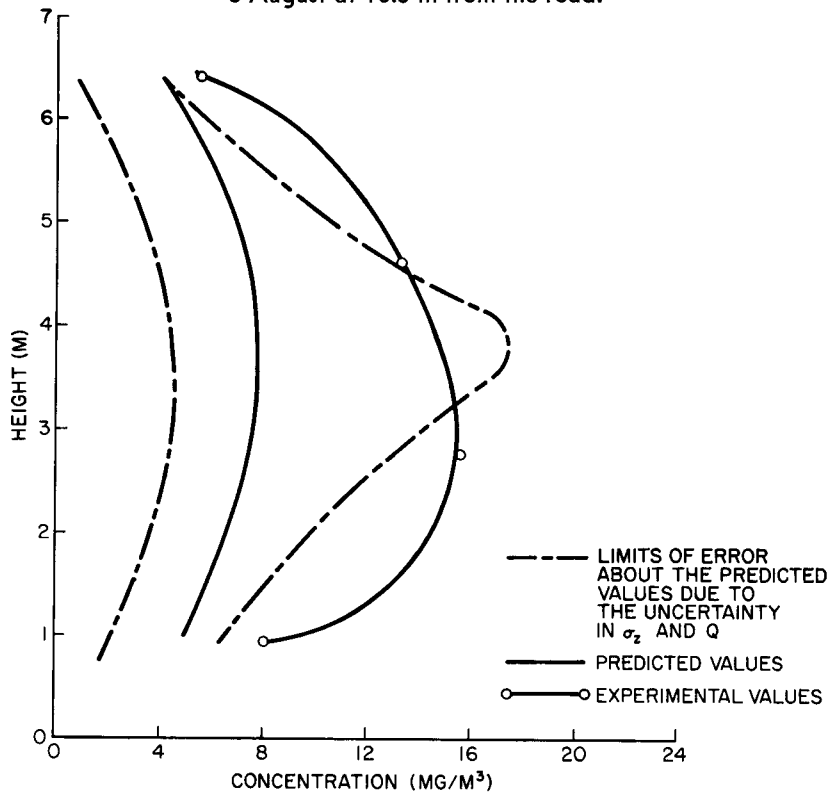


Figure 2.—A comparison of the theoretical versus experimental results on 6 August at 36.6 m from the road.

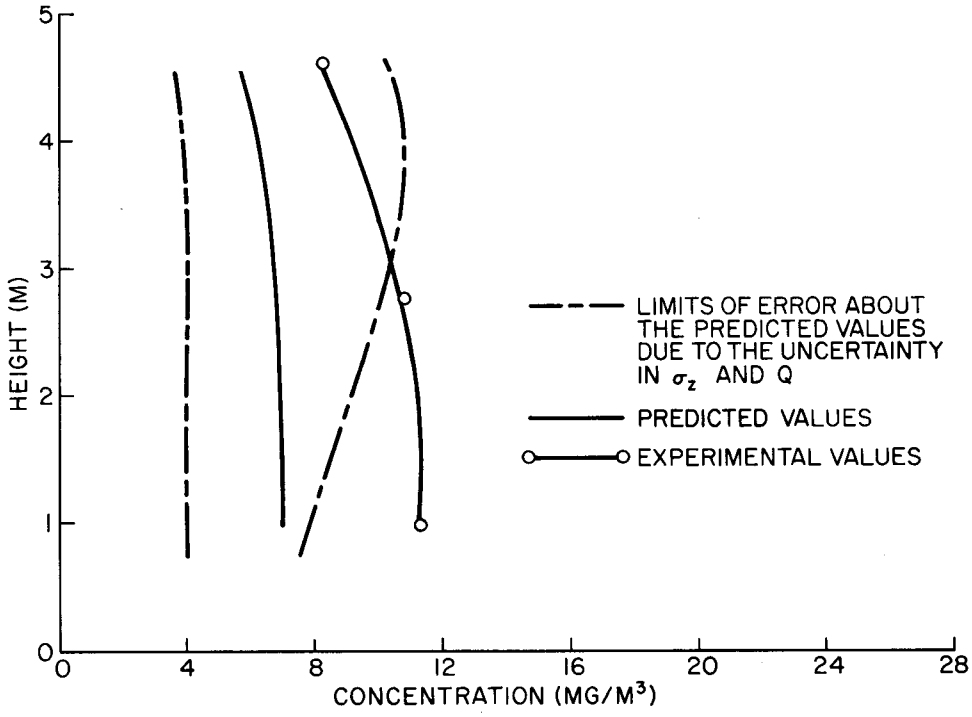


Figure 3.—A comparison of the theoretical versus experimental results on 15 August at 18.3 m from the road.

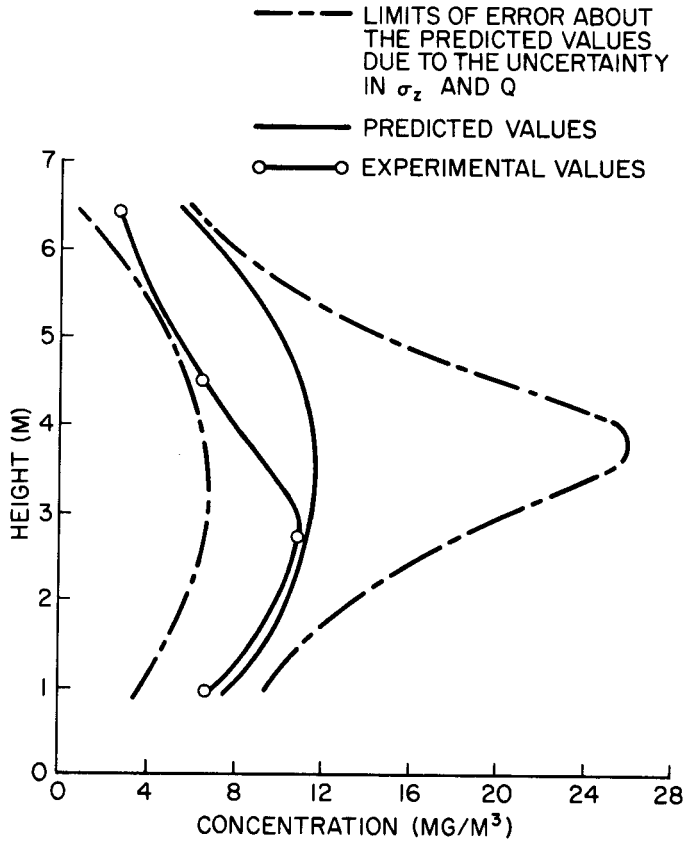
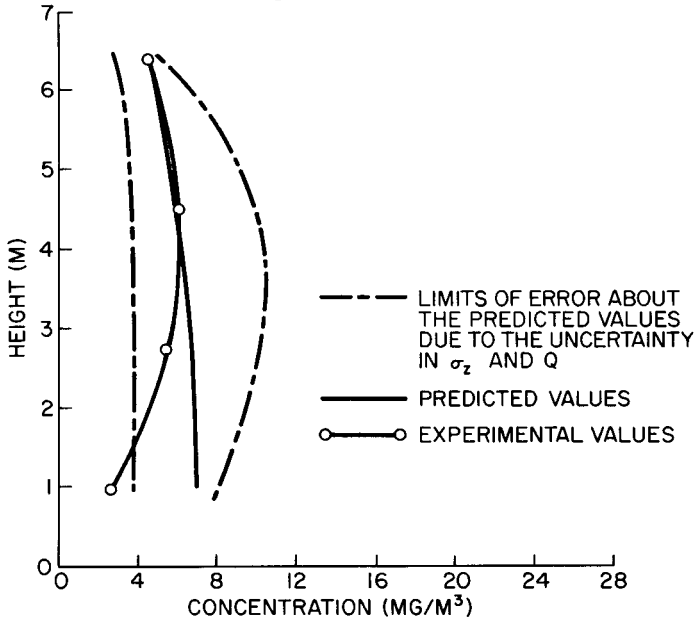


Figure 4.—A comparison of the theoretical versus experimental results on 15 August at 36.6 m from the road.



EXPERIMENTAL VERIFICATION OF THE PREDICTIVE MODEL

To test the validity of the predictive model, an experiment was designed to sample the dust cloud generated by a vehicle travelling on a gravel road. A 1000-foot straight section of gravel road giving access to farm lands provided the fugitive dust source. A vehicle of height equal to 6 feet travelled the road at a controlled speed of 30 mph and a frequency of two passes per minute. A classification of the gravel size was determined by sieving. The maximum size stone comprising the road was ½ inch, and 3.7 percent of the total sample mass was particles of less than 88 micrometers.

The dust plume was sampled in a plowed field downwind from the road. Concentrations in the plume were obtained at a fixed distance downwind by open-faced filters mounted at four elevations above the ground on a stationary support. Two vertical concentration profiles were attained on 6 August 1974 at 18.3 m (60 feet) and at 36.6 m (120 feet) downwind from the road. Again on 15 August, two vertical profiles were obtained at the same downwind distances. The samples were drawn for 10 minutes at 3.5 1pm on 6 August and for 20 minutes at 7.7 1pm on 15 August. Both sampling days could be classified as B stability with wind speeds of 2 m/sec.

A comparison of the concentrations as estimated with Equations 2 and 3 and the experimentally measured concentrations, both at the above given conditions, was made for all four experimental profiles (fig. 1 to 4). The predicted concentrations were found to be within a factor of 2 for 11 of the 15 measurements and within a factor of 3 for all measurements. The combined limits of accuracy suggested for σ_z *(Turner 1970)* and for the emission factor *(Roberts 1973)* accounted partially for the variation between experiment and theory. Turner suggested that σ_z may be expected to be correct within a factor of 2 in all stabilities provided one was only considering diffusion within approximately 200 m of the source. Roberts reported a mean emission factor of 9 pounds/vehicle-mile with a 95-percent confidence interval from 8 to 10 pounds/vehicle-mile. Thus, the source strength in the predictive model had an error band of ± 1 pound/vehicle-mile times the frequency of vehicle passage. The theoretical bands of error due to the uncertainty in both σ_z and Q are also portrayed in figures 1 to 4.

APPLICATION OF THE PREDICTIVE MODEL

Equations 2 and 3 were solved simultaneously under selected conditions (fig. 5 and 6). Figure 5 portrays the variation with x of the concentration at a height of 2.7 m for various wind-road angles. Two important conclusions can be drawn. First, the effect of wind-road angle on the downwind concentration under the given meteorological conditions and for the given aerosol parameters was negligible beyond 100 m. Second, up to 100 m from the road, the concentration increased as the wind direction shifted from perpendicular to parallel to the road. Figure 6 shows the variation with x of the concentration at a height of 2.7 m, given various particle sizes. The conclusion to be drawn from this graph is obvious. The concentration decreases with x more rapidly as the particle size increases. In terms of deposition, the above result can be understood by considering that larger particles are removed from the plume at a more rapid rate than smaller particles.

CONCLUSION

The predictive model yields concentrations within a factor of 3 of the actual concentrations. Given the meteorological conditions, a highway engineer or air-pollution engineer concerned with the local effect of a proposed unpaved surface on local inhabitants can use equa-

Figure 5.—The variation of concentration with distance perpendicular to the road for various wind-road angles.

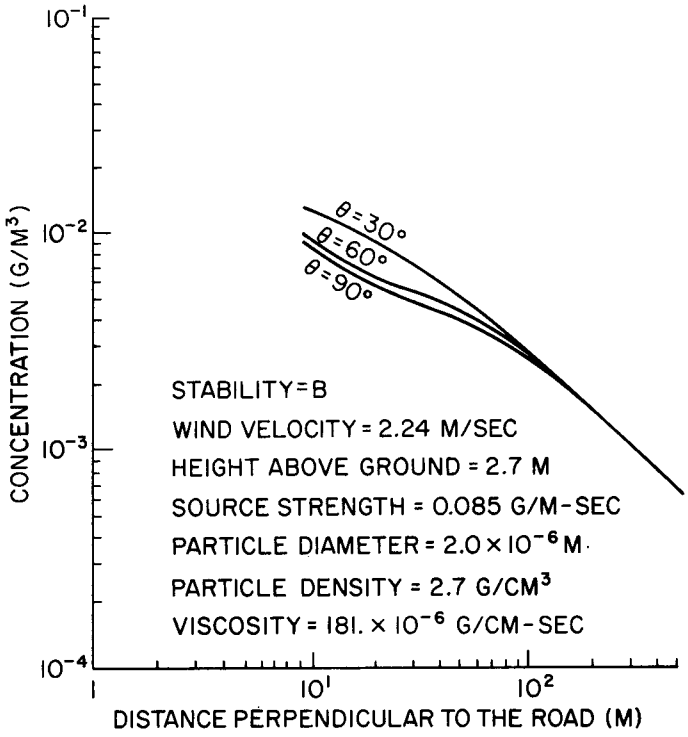
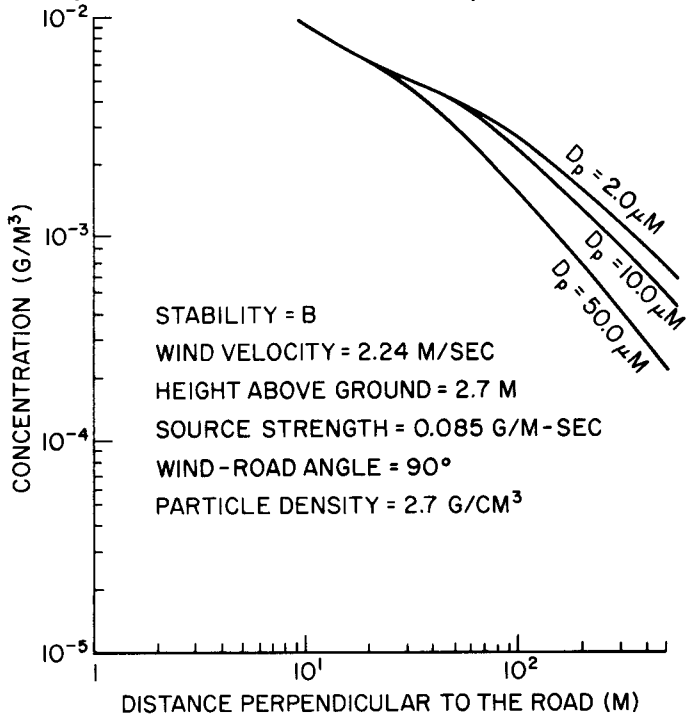


Figure 6.—The variation of concentration with distance perpendicular to the road for various particle sizes.



tions 2 and 3, along with Robert's total emission factors, to determine whether detrimental particulate concentrations might exist. Furthermore, this method can be applied just as readily to fugitive dust from paved surfaces. Roberts determined an emission from a paved surface travelled by a vehicle at 30 mph. More extensive research on emission factors from paved roads and at different vehicle speeds is needed before extensive application of this model can be made to paved surfaces.

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Acknowledgment. Appreciation is extended to the Center for Air Environment Studies and the Department of Mechanical Engineering of The Pennsylvania State University, without whose financial assistance this research would have been difficult to accomplish. This investigation was also supported by the Graduate Air Pollution Training Program, Office of Air Programs, Environmental Protection Agency, Grant No. T900011, administered through the Center for Air Environment Studies of The Pennsylvania State University. The report is Center for Air Environment Studies CAES Publication 411-75.

VEGETATION AND AIR QUALITY

Air Quality as Reflected by Injury to Metropolitan Vegetation

by A. F. RHOADS *and* E. BRENNAN, *graduate student and associate research professor, respectively, Department of Plant Biology, Cook College, Rutgers, The State University of New Jersey, New Brunswick, N. J. 08903.* *This is a paper of the Journal Series, New Jersey Agricultural Experiment Station, Cook College, Rutgers University. This research was supported by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Studies.*

ABSTRACT.—Chemical monitoring is the classical way of defining air quality. However, the ability of plants to reflect changes in air quality must not be overlooked because certain species respond in definite ways to gaseous pollutants. In New Jersey, chemical-monitoring data and plant-injury data have proved supportive for SO_2. While oxidant concentrations seemed to agree with plant data, recent changes in monitoring procedures have made the relationship unclear. Plant data have provided the only evidence for the presence of toxic amounts of fluoride in the air and have warned of the existence of as yet unidentifed substances that impair air quality.

EVALUATION OF AIR QUALITY of an urban environment can be based on two criteria: chemical data obtained by standard monitoring procedures and biological data collected in health and vegetation studies. Ideally, for each pollutant one would like to know the concentration present in the ambient air and the response that it elicited in a sensitive receptor, be it human or plant. Having been concerned with both types of evidence in New Jersey, we will discuss three kinds of situations we have encountered.

Before we do this, it might be appropriate to indicate just how urban an environment New Jersey is. The Garden State has a modest area of 7,836 square miles and a population of more than 7 million people squeezed into it — a density of 953 people per square mile, the highest in the Nation. The number of registered motor vehicles is more than 3.5 million, a density of 492 per square mile.

SULFUR DIOXIDE DATA IN AGREEMENT

The first situation is one in which monitoring data for the concentration of a pollutant in the ambient air are in agreement with plant-injury observations, and this involves sulfur dioxide (SO_2).

Sulfur dioxide has a long history of damage to vegetation in many parts of the United States. The major sources of SO_2 emissions in New Jersey are shown in table 1. However, since 1968 New Jersey has had in effect regulations

Table 1.—Sources of SO_2 emitted into the air in New Jersey in 1970

Source	Proportion attributed
	Percent
Power plant fuel	45
Commercial and industrial fuel	27
Residential fuel	12
Manufacturing processes	9
Transportation	6
Incineration	1

Source: New Jersey Department of Environmental Protection.

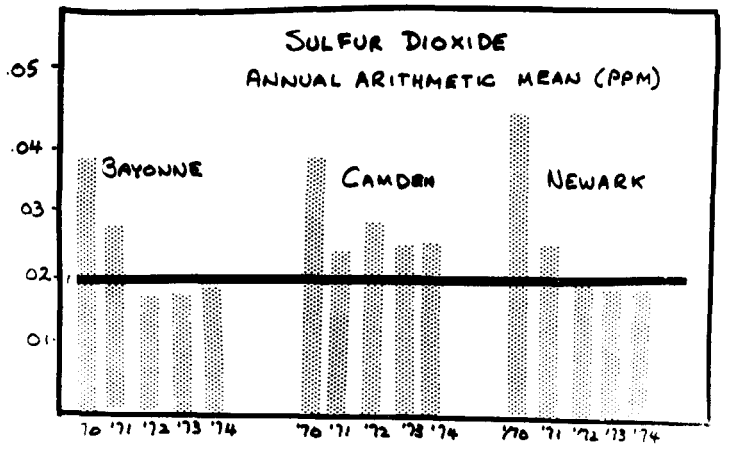
controlling the sulfur content of fuels used in the State. These regulations have been very effective in reducing SO_2 content of the air, as can be seen in the figures from the New Jersey Department of Environmental Protection Air Monitoring System for three locations in the State (fig. 1). Ambient SO_2 concentrations are now at or below the federal standard of 0.03 ppm maximum annual average. In the 2½ years during which we have been conducting a state-wide survey of air-pollution damage to woody plants, SO_2 injury has been notable for its absence.

Even when we made it a point to visit the site of power-generating stations, some of which burn coal and some oil, we were unable to find SO_2 damage on normally sensitive plant species such as crabapple *(Malus sp.)*, birch *(Betula spp.)*, zinnia *(Zinia elegans)*, tomato *(Lycopersicon esculentum)*, blackberry *(Rubus spp.)*, and white pine *(Pinus strobus)*. Inspection trips were made to the vicinity of six power plants in June 1974 and two others in July 1975. These stations were located in urban, relatively suburban and rural settings. The only site where probable SO_2 injury was observed was in northwestern New Jersey at a Christmas tree plantation 1½ miles downwind of a Pennsylvania power-generating station. Pennsylvania hasn't as rigid restrictions on sulfur content of fuels as New Jersey. It remains to be seen what will happen in terms of plant damage now that economic pressures have forced a relaxation of the regulations in New Jersey. At this time we can conclude that the chemical and biological data in respect to SO_2 are supportive.

OZONE-OXIDANT SITUATION UNCLEAR

Until 2 years ago we would have stated that the data for oxidant concentrations and plant damage are generally in agreement. Air-quality

Figure 1.—Ambient SO_2 concentrations (annual mean) in three New Jersey cities, 1970-74. Source: New Jersey Department of Environmental Protection.



standards for ozone were established in 1970 at 0.08 ppm as an maximum hourly average based on data obtained with the Mast (Mast Development Co., Davenport, Iowa) total oxidant meter. In New Jersey we have consistently observed ozone damage on sensitive species such as bean and tobacco following elevated Mast readings. A study conducted simultaneously at several locations in the Northeast attempted to correlate Mast total oxidant-monitoring data with injury to ozone-sensitive Bel W-3 tobacco *(Jacobson and Feder 1974)*. Although there were some variations, generally the most severe tobacco injury occurred at the sites that also had the greatest number of high Mast readings. However, recent changes in the monitoring technique required by the Environmental Protection Agency (EPA) have complicated the picture.

EPA has specified a chemiluminescent procedure as the required method of ozone monitoring. Unlike the Mast meter, it is specific for ozone, the major component of the total oxidant complex. Since New Jersey air-monitoring facilities replaced Mast meters with chemiluminescent devices in 1973, the apparent ozone level in ambient air has increased. This increase has not been accompanied by a discernible increase in plant injury. As far as we know, no one has systematically compared ozone levels obtained by a chemiluminescent technique and plant response. Until this is done, we will not know the significance of the data in terms of effects on sensitive plant species. Since primary and secondary air-quality standards are based on effects on human health and plant life or property, respectively, it would seem of the greatest importance to resolve this matter as soon as possible and establish new standards based on new monitoring technology if that proves necessary.

Meanwhile we do have evidence from our observations of sensitive plant species that an ozone problem exists in New Jersey, whatever the magnitude of the concentrations. Plantings of beans at New Brunswick and the Rutgers South Jersey Research Center in 1974 and 1975 provide ample evidence of damaging levels of ozone. Ozone fleck on white pine also occurs throughout the State. In addition, we commonly observe a dark upper-surface stipple on ash *(Fraxinus americana)*, zelkova *(Zelkova serrata)*, dogwood *(Cornus florida, C. stolonifera)*, and linden *(Tilia tomentosa, T. europaea, T. enchlora)* developing in midsummer. This symptom is similar to ozone toxicity symptoms on herbaceous species such as bean. However, more experimentation is necessary to determine to what extent ozone or other stresses are involved in this symptom development.

Further controversy has recently been injected into the ozone-oxidant picture with the finding that certain remote rural sites show surprisingly high ozone levels. Various hypotheses, including natural sources, long-distance transport from urban areas, and consumption of ozone in urban atmospheres, have been proposed to account for these high levels. Again a correlation with plant injury is lacking. Simultaneous observations of sensitive plants could help to clarify the significance of these monitoring data. With ozone we therefore have a situation where there is a demonstrated need for the simultaneous collection of monitoring data for pollutant concentration as determined by chemiluminescent procedures and of plant-injury data.

PLANTS LEAD THE WAY

The third type of situation is the case where injury to plants is our only definitive clue to the presence of injurious substances in the air. Hydrogen fluoride (HF) is a case in point. The New Jersey Department of Environment Protection does not monitor HF because the state has not established standards for atmospheric fluorides. Statewide surveys of

air-pollution damage to agronomic crops conducted in 1971 and 1972 showed HF damage amounting to 3 percent and 18 percent of the total losses, respectively *(Feliciano 1971, Pell 1973)*. Characteristic HF damage to woody and herbaceous plants continues to reflect the presence of toxic levels of this pollutant. In 1974 HF was the major cause of air-pollution damage to woody vegetation in the state *(Rhoads and Brennan 1975)*. Fluoride injury appeared as marginal scorch on a variety of species, including gladiolus, *(Gladiolus* hyb.), wild cherry *(Prunus virginiana)*, grape *(Vitis labrusca)*, linden *(Tilia americana)*, blueberry *(Gaylussacia spp.)*, and aspen *(Populus tremuloides)* and as tip necrosis of various coniferous trees. Even oaks *(Quercus alba, Q. velutina,* and *Q. prinoides)*, which are considered only moderately sensitive to fluorides, were severely injured. Trees showing resistance during this extreme episode included *Acer platanoides, Ilex opaca, Malus* spp., and *Betula populifolia*. Tissue analyses of leaf samples collected in the affected area helped to pinpoint atmospheric fluorides as the cause of the injury, and gave homeowners whose plants had been affected the local industrial sources. Unfortunately it is not possible to make a quantitative estimate of ambient HF concentrations from tissue fluoride levels. Monitoring procedures for the pollutant must be initiated.

UNKNOWN POLLUTANTS

We have encountered another type of situation where we have neither chemical air-monitoring data nor specific plant data. We know that plants are being injured by some air pollutant, but we do not know its identity. One case involves a distinctive tip injury on Austrian pine *(Pinus nigra)* which is always delimited by a dark band at the base of the necrotic area *(Brennan and Davis 1967)*. This symptom occurs on certain sensitive trees year after year, with varying severity. Other neighboring trees are consistently resistant to whatever the causal factor is. We have evidence for an atmospheric cause of the Austrian pine tip-burn symptom as a result of the use of two open-top air-pollution modules, one supplied with charcoal-filtered air and the other with unfiltered ambient air *(Mandl et al. 1973)*. Using grafted trees prepared from scions of mature Austrian pines showing sensitivity and resistance to this sympton, we have shown that the incidence of tip burn was much greater on the sensitive grafts grown in the unfiltered module than on those in the filtered module or on the resistant grafts. We have been unable to duplicate this symptom through controlled fumigations with O_3, SO_2, or a combination of O_3 and SO_2. The combination approximates the symptom, but the dark band does not become evident until 3 or 4 weeks after fumigation.

In summary, we emphasize the necessity of using both chemical monitoring devices and biological systems to evaluate air quality. Chemical monitoring alone may yield data on ambient levels of many different pollutants. However, unless we can relate these levels to effects on receptors, they are meaningless abstractions. Plants alone are not a satisfactory monitoring system, for although most pollutants elicit a characteristic response, it is too easily affected by other environmental variables *(Pell and Brennan 1975)*. Our observations in New Jersey indicate that, at present, monitoring data and plant effects are well correlated in the case of SO_2. The ozone-oxidant situation is not as clear. Recent mandated changes in monitoring techniques require a reassessment of the degree of plant injury associated with certain ozone levels. In the third instance we find plant data yielding information about a pollutant, HF, which probably should be included in a monitoring program. And finally, we see reflected in vegetation the presence of

as yet unidentified chemical substances in the atmosphere that are indicative of further impairment of air quality.

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Sulfur Pollution : An Environmental Study of Welland, Ontario

by MICHAEL R. MOSS, *assistant professor, Department of Geography, University of Guelph, Guelph, Ontario, Canada.*

ABSTRACT.—The distribution of sulfur as an environmental pollutant is analysed in the vicinity of Welland, Ontario. A biogeochemical-cycle approach enables areas of excess accumulation to be compared among all linked ecosystem components. Although the patterns of distribution are similar, the amounts of sulfur accumulated in different ecosystems, grassland and woodland, show marked contrasts. The significance of these findings to urban and rural land-use planning is considered.

THE PAST DECADE has produced a tremendous explosion of information about all aspects of pollution. In spite of this there seems to be a major gap in our knowledge or an inability to apply our knowledge of the effects of pollutants within a total environment. This is particularly true in terms of terrestrial environments, yet there is a large volume of material on the effects of individual pollutants upon the separate components of these environments.

Although environment-impact statements are often a prerequisite for planned development of the human environment, the spatial impact of pollution upon the environment is often neglected. With the current rapid rate of urban growth in such places as southern Ontario, the impact of the urban physical environment system upon rural areas will undoubtedly increase.

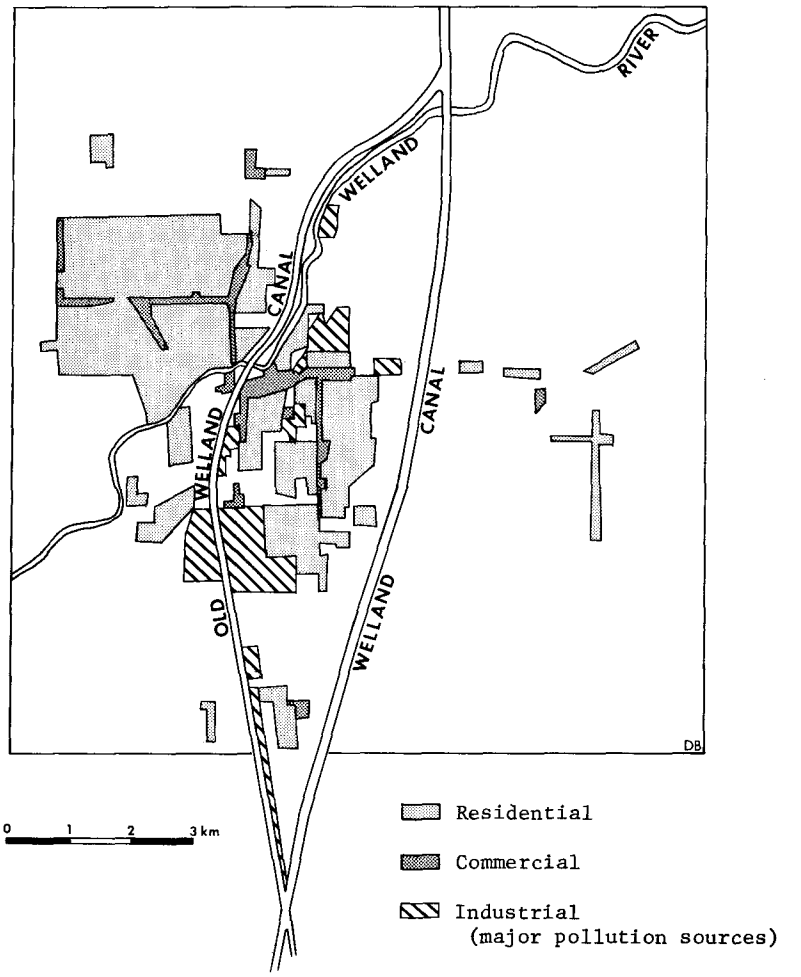
This impact will be most evident in the rural/urban fringe areas of existing urban centres. Yet it is also in these fringe areas that there will be the greatest demands for residential expansion, recreational facilities, and improved standards of environmental quality. This is a report on an attempt to identify the impact of one pollutant, sulfur, upon the total physical environment of Welland, Ontario, and to show how an integrated approach to such a problem can benefit the planning of urban expansion and amenities in the surrounding area.

THE AREA

The city of Welland, Ontario, and its immediate hinterland provide an ideal site for a spatial impact study. Welland is a moderate-size urban center (population about 50,000), which is heavily industrialized, having several major steel-producing and metallurgical industries centrally located in an elongated belt paralleling the Old Welland Canal (fig. 1). Furthermore, the city is sufficiently isolated from other major urban/industrial centers such as Hamilton, Ontario (48 km northwest) and Buffalo, New York (24 km east) to remain reasonably free from any influence from such centers. The Welland area also lacks any major topographic barriers — being located on the Haldimand Clay Plain and at a point sufficiently far inland to avoid any significant lake-breeze effects from either Lake Erie (10 km south) or Lake Ontario (22 km north).

It is an area of declining agricultural importance, yet there remain several viable truck farming operations to the northwest. Soils are generally rather poorly drained clays, clay loams, and silty clay loams. Locally they are low-quality soils, but in a broader regional or national context they are classed as

Figure 1.—The city of Welland, Ontario, showing the distribution of major urban land-use types.



soils with only moderate limitations to their future re-use and are therefore of reasonable potential.

Residential expansion is currently thrusting in a northward direction, but further expansion is likely to be to both east and west of the built-up area. Ribbon development is now a common feature along many of the rural roads, and increasing housing demands within the region will no doubt heighten the problem.

Furthermore, to accommodate this expanding urban population, the area (fig. 1) contains five separate locations with high recreational potential, three areas that are unique biological sites, and the banks of the Welland Canals with their recreational potential *(Philips Planning and Engineering 1971a)*.

Planners of human space and environmental quality should be aware of the condition of the physical environment because this will directly affect the amenities outlined above. Since all these amenities are themselves components of the environmental system, it follows that man's impact upon this system (in this case as pollution) should be undertaken from the point of view of a sys-

tem analysis of the total environmental system. This can be achieved through an ecosystem analysis.

THE APPROACH

An ecosystem approach should provide the most substantial and meaningful studies of environmental pollution *(Moss 1976)*. In this way the biogeochemical cycles, which are a natural functioning part of any ecosystem, can be used as models that naturally perform an integrative function in linking all environmental components. Excess quantities of any biogeochemical element that can be shown to disrupt the normal functioning of any ecosystem can be said to be pollutants. In addition, the biogeochemical cycles provide the necessary information about the precise form of the pollution element to be measured in any one ecosystem component.

By the established pathways taken by such elements, the links from component to component can be identified. At the same time a knowledge of the normal concentration of each element in each component can be used as a measure against which excess concentrations may be noted. It is the effects of such excesses that are considered pollution. Measurement of the distribution of concentrations would therefore identify the spatial impact of a pollutant upon an area.

SULFUR IN THE WELLAND ENVIRONMENT

The approach outlined above will identify the sulfur cycle as a pollution model to be utilized in an environmental context. In almost every ecosystem, sulfur is made available quite naturally either by weathering of bedrock or by absorption of gaseous sulfur from the atmosphere. This system is disrupted in locations where excess amounts of sulfur are injected into the atmospheric component, primarily as SO_2, as a result of fossil fuel combustion and industrial processes. This may be viewed in ecosystem terms as a new pathway introduced into the sulfur cycle, that is, sulfur from the lithosphere reaching the biotic component via the atmosphere in much greater quantities and over a much shorter time span than it possibly could under natural circumstances *(Moss 1976)*.

The sources of excess sulfur in Welland are primarily industrial (fig. 1). In 1968 (the last year for which complete data are available) some 1903 tons were injected into the atmosphere. Of this total, 1,701.5 tons were emitted by industrial sources *(Ont. Dep. Energy and Resour. Manage. 1968)*. This survey of atmospheric sulfur was conducted for March through June, using 20 sites within the built-up area. The results obtained by the lead-peroxide method show a change from winter to summer concentrations with values as high as 1.20 mg SO_3/100 cm^2/day immediately to the east of the main source. More significant is the spatial pattern. In each month the highest values occur to the east, downwind of the major pollution sources. However, a secondary area of moderately high concentrations with values between 0.50 and 0.70 mg SO_3/100 cm^2/day is always present to the west of the Old Canal and extends over the western residential area and into the rural zone. A sharp decrease in values is encountered to the east of the main industrial zone, and a more gradual decline in values to the north and south.

From September 1973 to January 1974, I extended the survey area, using 15 stations primarily to the east of Welland and extending several miles into the rural area. The use of Huey plates provided data similar to that of the 1968 survey and showed the highest values obtained to be 1.22 mg SO_3/100 cm^2/day in January 1974 for the site equivalent to that mentioned above for the 1968 survey. Again the highest values of SO_3 were immediately east of the main source, and values decreased at varying rates from this peak. One major devia-

tion from this pattern, however, is encountered at distances approximately 4.8 to 6.4 km east of the source, where a zone of secondary concentration is encountered.

If the results of the two surveys are now combined to produce a pattern indicative of long-term conditions, then the distribution of atmospheric sulfur in the Welland area appears to be one of three fairly well defined and distinct areas of concentration (fig. 2). The most evident is the zone of high values encountered immediately east (downwind) of the major source. Here values greater than 1.00 mg SO_3/100 cm^2/day are encountered. This area is separated from the other two zones, which are due east and west, by troughs of fairly low mean values. Both secondary concentrations indicate values in the range > 0.50 to < 0.75 mg/100 cm^2/day. The area of secondary concentration to the east appears to be less prominent in fig. 2. than it actually is in each month because of its north-south migration over 4.8 or 6.4 kms. at different months.

Anthropogenically - produced atmospheric sulfur has several possible fates. Some will undoubtedly drift outside the immediate area, but the natural pathway for this atmospheric sulfur is to enter the biotic component of the environment either as gaseous SO_2 absorbed by soils and vegetation or as $SO_4^=$ deposition, mainly in precipitation to the soil surface and subsequently to plant roots *(Moss 1976, 1975a)*.

Soil samples from the A1 mineral soil horizon were collected from sites within 8.5 km of the main sources of atmospheric sulfur and were analyzed for $SO_4^=$ content by the barium sulfate turbidimetric technique. A total of 26 sites were used, the majority to the east of the city. When results are presented in graph form and plotted against distance from the source, some significant patterns emerge (fig. 3). The data show values to decrease with increasing distance from the source to a point about 4.0 km and then subsequently rise to a second and lower peak at about 6.4 km and then decrease. When woodland soils are distinguished from grassland soils this trend is particularly marked in woodland soils, the grasslands showing greater variation near to the source.

Figure 2.—Schematic representation of the seasonal average concentration of atmospheric sulfur over Welland and adjacent rural areas. Isolines drawn at 0.10 intervals, show SO_3/100 cm^2/day.

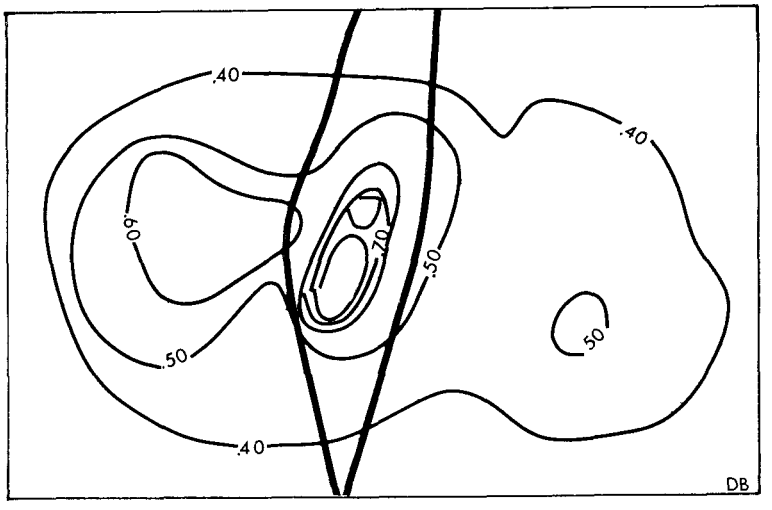
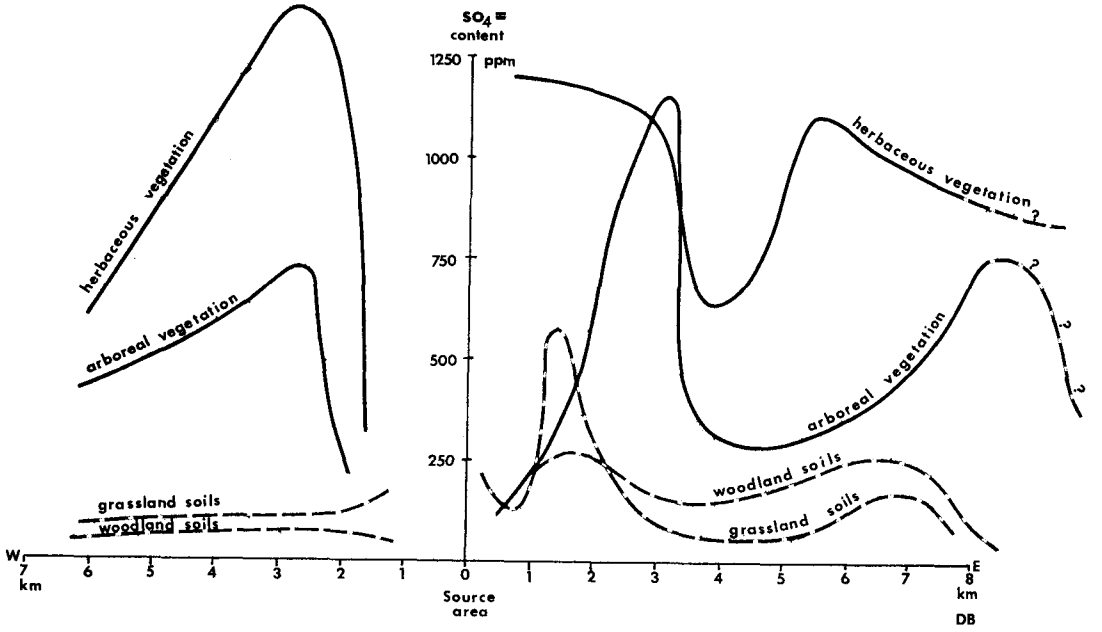


Figure 3.—The generalized distribution of sulfate in soils and vegetation samples with respect to distance from the main source area.



Data to the west are too sparse for any significant identification of trends because of fewer possible sampling points. The mean value for all soil $SO_4^=$ values is 134 ppm, which can be subdivided into one of 160 ppm (range 18 to 726 ppm: n=13) for grassland soils and 134 ppm (range 50 to 284 ppm: n=3) for woodland soils.

Vegetation was analyzed for $SO_4^=$ in related surveys, one of herbaceous vegetation growing in abandoned fields and one of leaf samples from woodland sites. The results of these analyses are included in figure 3. Complete data for both soils and vegetation and the cartographic presentation of results have been published *(Moss 1975a)*. Sites were the same as those used for soil sampling.

Herbaceous vegetation samples consisted of clippings of $1m^2$ quadrats, five for each location. Every effort was made to ensure uniformity of herbaceous species and age of abandonment.

The results for herbaceous vegetation show that, except for two points about 4.0 km from the source, the amounts decrease very slightly over 8.0 km in an easterly direction. Values obtained are consistently between 1,000 and 1,280 ppm $SO_4^=$ except at 4.0 km, where values fall to 588 and 802 ppm. To the west, the three locations sampled indicate a rise from 267 to 1,400 ppm over 0.6 km and a drop to 527 ppm at 6.1 km.

In sampling woodland vegetation, more consistency was possible in the materials sampled. In each case oak leaves were collected. Quantities measured ranged from 190 to 1,250 ppm and, as in the case of herbaceous vegetation, the pattern to the east showed two areas of relatively high values, one centered around 3.2 km and the other around 8.0 km from the source. To the west arboreal samples show a similar pattern to herbaceous vegetation.

Comparison between the arboreal and herbaceous data sets indicates that the mean concentration in herbaceous vegetation for all sites is 975 ppm (1047

ppm to the east, 731 ppm to the west). Mean values for arboreal samples is 546 ppm for all sites (576 to the east and 472 to the west). In seven cases herbaceous and arboreal samples were collected less than 0.4 km apart, yet in five of these cases the arboreal samples showed values to be about one-half or less of the herbaceous $SO_4^=$ values.

DISCUSSION

Though it is not possible to obtain statistically valid correlations in the spatial distributions of sulfur between either the atmosphere, the vegetation, or the soil, there is a remarkable correspondence in the nature of the distributions encountered. Both ecological and pedological reasons can be advanced for this lack of statistical relationship *(Moss 1975a)*. This result, however, differs from the similar work of Johansson *(1959)* and McGovern and Balsillie *(1972)*, who were able to show a straightforward linear relationship between distance from source and atmospheric sulfur and vegetation-accumulated sulfur. Lihnell *(1969)* found a somewhat irregular pattern in his results from using similar variables. What these contrasting results do show, however, is that in many cases individual locations have to be treated independently. Although there are established functional links between all environmental components, the patterns that emerge are determined primarily by the source and the atmospheric dynamics of the site. Successive stages in the movement of the pollutant from component to component will reflect this atmospheric spatial pattern.

In the Welland case the occurrence of three distinct areas of atmospheric sulfur concentration should have direct implications for any development in areas adjacent to the present built-up area. In terms of air-quality standards, continuous monitoring for sulfur oxides at the most heavily polluted site showed that in 1973 on no occasions did concentrations exceed Ontario criteria for desirable air quality *(Ont. Minist. Environ. 1973)*. But whereas sulfur in the atmosphere is relatively short-lived and there is a constant throughput when this passes to the next component, there will be build-up. Here, in the soils and vegetation, sulfur will accumulate over a long period of time; a growing season for vegetation and longer for soils. In both of these, local variables will determine accumulations. For Welland, where the atmospheric sulfur is not severe, values of soil sulfur reach 726 ppm. This is considerably higher than any value obtained in the heavily industrial Sheffield region in England *(Moss 1975a)*. For Trail, British Columbia, a mean of 185 ppm *(Katz et al 1939)* is not appreciably different from that of 134.12 ppm for Welland. For vegetation the Welland values appear to be extremely high when compared with, for example, data from industrial South Wales, where oak leaves yielded a high of 113 ppm at 2.4 km from a source.

The significant point from the above comparisons is, that to determine areas of environmental pollution requires an initial extensive survey to determine the extent of the atmospheric sulfur pattern, even in an area of relatively uniform surface topography. The quantities of the pollutant encountered in the next environmental component should reflect the atmospheric pattern although in different localities what may be acceptable limits in one component may be quite unacceptable in another.

Furthermore, there are obvious differences between the amounts of sulfur absorbed and accumulated by soils and vegetation between grassland and woodland ecosystems. The fact that grassland ecosystems appear to accumulate more sulfur could have significant repercussions on air hygiene in the area. The planting and maintenance of sulfur-tolerant grass species could be useful in land-use planning.

CONCLUSIONS

By identifying the spatial limits of potential pollution from the first stage of environment transfer — the atmosphere — the spatial limits of potential environmental pollution are set. In this way the erroneous and restricted limits of the area affected by air pollution recognised by local planning studies as being limited to two centers between the Old and New Welland Canals would be overcome *(Philips Planning and Engineering, 1971)*. Any other environmental components can only be vertically linked by the natural pathways. Differences in the reaction of these biotic components to accumulation can yield significant clues to the maintenance of viable ecosystems. Although concentrations and accumulations do not indicate pollution in the true sense, they do identify where pollution will occur. Thus the occurrence of higher values of sulfate being encountered in precipitation at 8 km from the source than at 4 km from the source, and the significance this has for precipitation pH, can be explained *(Moss 1975b)*. Only by such a method can a more meaningful environmental approach to environmental planning be initiated.

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Landfill Gases and Some Effects on Vegetation

by FRANKLIN B. FLOWER, IDA A. LEONE, EDWARD F. GILMAN, *and* JOHN J. ARTHUR, *Cook College, Rutgers University, New Brunswick, N. J. 08903. Flower is extension specialist in environmental science, New Jersey Cooperative Extension Service; Leone is professor, Department of Plant Biology; and Gilman and Arthur are research assistants in Plant Biology.*

ABSTRACT.—Gases moving from refuse landfills through soil were studied in New Jersey. The gases, products of anaerobic decomposition of organic matter in the refuse, caused injury and death of peach trees, ornamentals, and commercial farm crops, and create possible hazards to life and property because of the entrance of combustible gases into residences. Remedial measures are described.

THREE REFUSE LANDFILLS in New Jersey have been under study for the past 6 years because underground gases from the landfills have been moving through the soil into adjacent areas and damaging vegetation.

The New Jersey Cooperative Extension Service, charged with responsibility for responding directly to the needs of the state's citizens, becomes involved with various kinds of problems. One of these has been the underground generation and movement of combustible gases, carbon dioxide, and the odorous gases of sulfur reduction. Although there are many different sources for these gases, we have been working with those arising from the decomposition of organic matter in commercial refuse landfills.

The members of the Rutgers-Cook College faculty who have been involved in these studies include a specialist in environmental sciences, county agents, plant pathologists, entomologists, and soil scientists. In addition, whenever possible we have involved the staffs of the state, county, and municipal health departments, the New Jersey Bureau of Solid Waste Management, the federal solid waste management programs, the owners and operators of the various refuse landfills, and the owners of the properties affected.

The problems described in this paper include the death of peach trees in a commercial peach orchard in Gloucester County, the death of ornamental vegetation in Camden County, and damage to commercial farm crops in Burlington County. All are located in the southwestern quarter of the state. In addition to the death of vegetation, the Camden County case involved a hazard to life and property because of the entrance of combustible gases into private residences adjacent to the landfill.

THREE LANDFILL CASES

The three landfill cases we have followed most extensively during the past 6 years are in Glassboro, Gloucester County; Cherry Hill, Camden County; and Cinnaminson, Burlington County. All were brought to the senior author's attention by Rutgers County Agents responding to complaints of vegetation injury and death from unknown causes. All three cases were associated with landfills where refuse had been deposited in worked-out sand and gravel pits.

Glassboro

The landfill in Glassboro covered about 6 acres. The refuse, which consisted of household and industrial wastes, demolition materials, and sewage

sludge, was deposited to depths of 10 to 20 feet. A commercial peach orchard abutted the landfill along about 1,000 feet of its periphery. The balance of the landfill was adjacent to scrub vegetation on land that was apparently not serving any commercial, agricultural, or residential use.

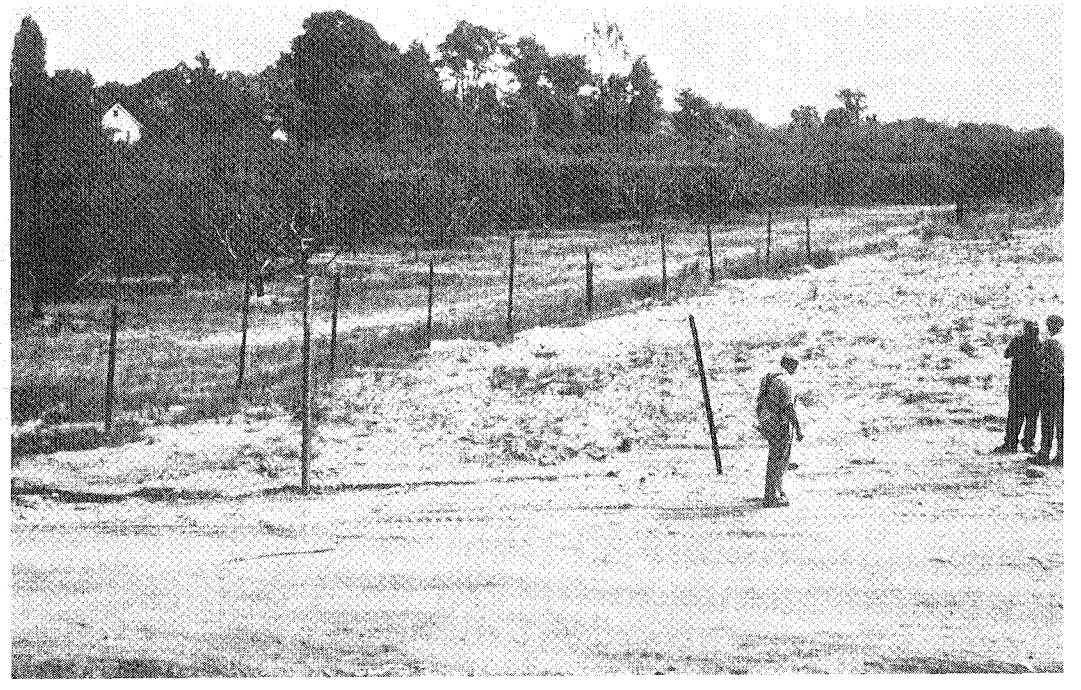
Landfilling at this site began in February 1968. Refuse deposition along the northeast line of the landfill adjacent to the peach orchard was completed in 1969. The peach trees nearest this line began dying during the summer of 1971. Our first inspection of this site was made in September 1972. By that time about 50 peach trees had died (fig. 1). Combustible gases and carbon dioxide were found, along with low oxygen concentrations, in the root zones of most of these dead peach trees. The greatest distance of these dead peach trees from the landfill was 70 feet.

In March 1974, landfill gases were found more than 80 feet from the landfill. By then about 70 peach trees had died. The peach farmer brought the operator of the landfill (the Borough of Glassboro) into the Chancery Division of the Superior Court of New Jersey, and after a week of testimony the case was settled out of court to the plaintiff's satisfaction.

The landfill and peach orchard were examined again in the early summer of 1975. The landfilling was complete and appeared to have an adequate cover of soil material. Some minor settlement had taken place, causing surface water puddles to form. More than half of the mature peach trees adjacent to the landfill in 1971 had been removed as part of the farming procedure and were replaced in 1973-74 with new trees. However, the young trees in the row nearest the landfill died and were replaced with new trees. These too died, in the spring of 1975.

No corrective measures have been taken to reduce the lateral movement of

Figure 1.—Commercial peach orchard adjacent to completed refuse landfill in Glassboro, N. J. Dead peach trees can be seen in the rows nearest the landfill in foreground.



these gases. We expect that the farmer will continue to lose peach trees planted near the landfill.

Cherry Hill, Camden County

This 9- to 10-acre landfill is surrounded by 28 single-family homes that were constructed before landfill operations began. Refuse 10 to 60 feet deep has been deposited in this former sand and gravel pit. When dumping began in the fall of 1963, only bulky wastes and demolition materials were being deposited. However, the nature of the materials being deposited gradually changed later to include general municipal refuse and garbage. Dumping was completed in 1970, and Cherry Hill Township has since been making efforts to turn this former landfill into a municipal park. The fill had been placed in a manner to incorporate esthetically pleasing hills and slopes within the park perimeter; topsoil has been brought in, and the area has been seeded.

We were first called to this area by the Rutgers Camden County Agricultural Agent in January 1969 to help determine the cause of vegetation death in the backyard of a home abutting the landfill. A spruce tree, rhododendron, Japanese yew, azaleas, dogwood trees, flowering peach trees, Scotch broom, arborvitae, Douglas-fir, and an area of lawn grass had recently died. Our soil gas tests indicated the presence of combustible gases, carbon dioxide, putrid ground odors, and the lack of oxygen.

Periodic checks made in this area revealed that vegetation injury and deaths seemed to be progressing gradually from the landfill toward the houses. In June 1971 a general inspection of the entire area indicated that there were clumps of dead vegetation at various points around the entire periphery of the landfill. At this time it was recommended that the responsible government officials check the complete landfill to see if gases might be migrating from the landfill into backyards and toward other homes.

Between December 1971 and January 1973, four different 10- to 15-foot deep stone trenches were installed in an effort to prevent the lateral movement of gases from the landfill to the adjacent properties. Only some of these trenches were successful in stopping this. In April 1974 the legal case between a dozen residents and Cherry Hill Township, the owner and operator of the landfill, was heard in the Chancery Division of the Superior Court of New Jersey. After a week of testimony the case was settled out of court. The plaintiffs received $60,000 in settlement. In addition, the township was required to vent the landfill gases from the periphery of the landfill.

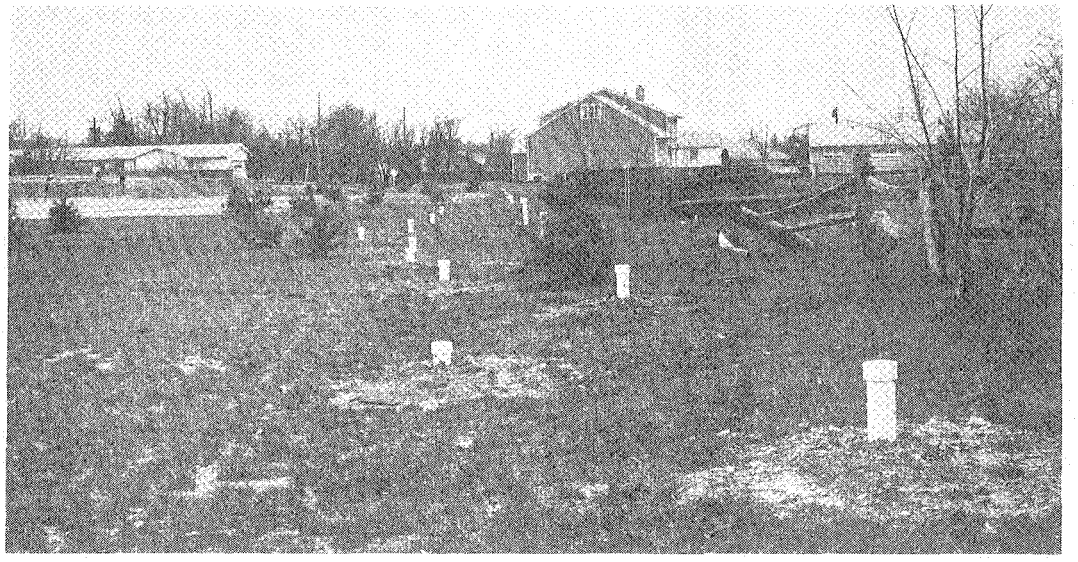
In the fall of 1974 vertical venting pipes were installed on the periphery of the landfill (fig. 2). Many of the vent pipes along the eastern periphery of the landfill have been vandalized and the tops broken by rocks. However, it did not appear that the vandalism decreased the efficiency of these plastic pipes for gas venting.

In April 1974 a single maple tree was planted in the lower elevations of this landfill park. No sign of this maple tree could be found in March 1975. It had disappeared. Only one clump of naturally seeded trees was noted in the spring of 1974. This was a group of maple trees that have been growing for a number of years near the southeastern corner of the landfill. Tests indicated that gases of anaerobic decomposition were not present in the root zone of these trees.

Examination of the landfill park in spring 1975 revealed that a large number of deciduous and evergreen trees had been planted over much of the park area the previous fall. Species included sweet gum, red oak, crab apple, Japanese poplar, white pine, Scotch pine, and fir. No trees were planted on the tops of the high refuse hills.

As of March 1975 many of the evergreen trees looked brown. There were

Figure 2.—Vertical gas venting pipes in place along the periphery of the landfill in Cherry Hill, N. J. Newly planted trees for landscaping are also shown.



also signs of vandalism: some trees had been pulled from the ground; others had limbs broken off; and some had apparently been stolen. The holes left after the trees had been pulled or dug from the ground appeared to be rather shallow, and the soil beneath them appeared to be very well sealed since water puddles remained in them some days after a heavy rain. Examination of these trees indicated that many of the dead trees did not live because of poor planting practice. Only a limited number of the trees revealed the presence of the combustible gases in their root zone.

During the last half dozen years the vegetation in the backyard of the home has continued to die until only that vegetation near the home remains. It will be interesting to see if the gas vents prevent further gas intrusion into these adjacent lands and permit vegetation growth again. We plan to periodically monitor these plantings to see if the landfill gases present any future problems. Perhaps the vertical vents will alleviate the problem at this location.

Cinnaminson in Burlington County

A landfill in which refuse has been placed to depths of 80 feet on about 100 acres is operating on the northern side of Union Landing Road. A 600-foot-long road interface exists between the landfill and the farm on the southerly side of Union Landing Road. The distance between the edge of the farm and the edge of the landfill is 50 to 60 feet. This space is occupied by Union Landing Road and its right of way. Apparently all sorts of refuse materials have been accepted by the landfill, which began operation about 1965.

In the summer of 1970 the farmer experienced difficulty in growing tomatoes in fields nearest the landfill. Very unpleasant odors, arising from the area of his field nearest Union Landing Road, were noted by the farmer during the spring plowing of 1971. At that time we examined this field for possible problems associated with the landfill. In the fall of 1971 decomposition gases were discovered 300 feet from the landfill. Since the spring of 1971 the farmer has

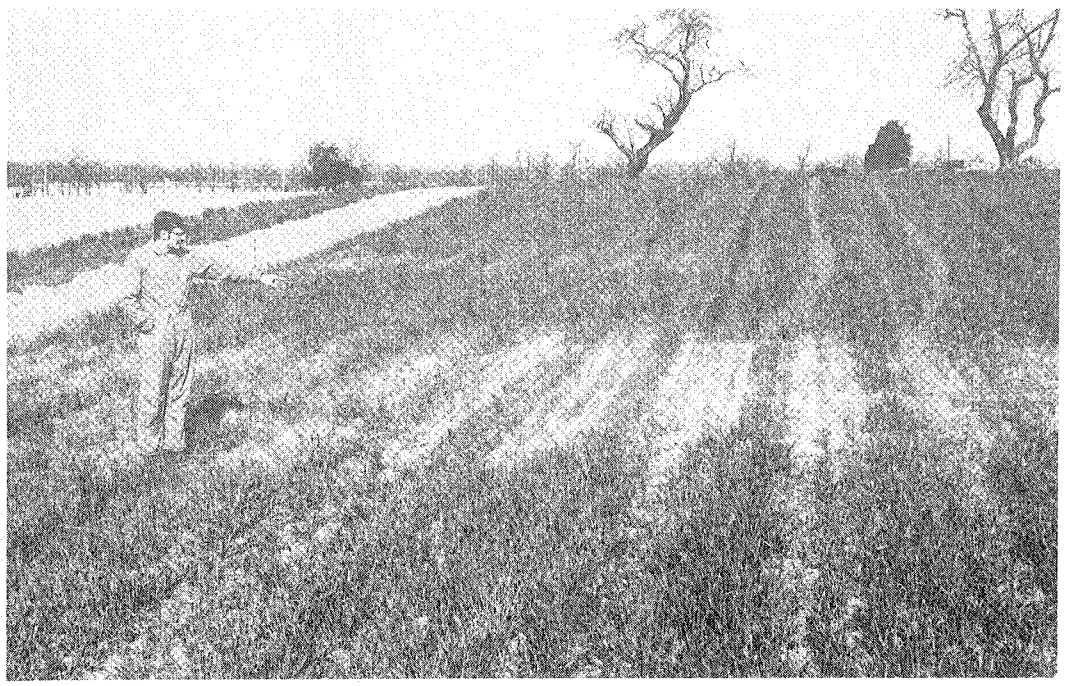
not cultivated the 2 to 3 acres of his fields nearest Union Landing Road. The death of vegetation in the field resulted in erosion of the surface of the field, and a weed cover crop developed.

By the fall of 1971, the landfill operator had recognized that his landfill was the source of the farmer's problem. He then installed a 600-foot-long, 10-foot-deep, 3-foot-wide gravel-filled trench the total length of the interface between the landfill and the farm. This did not seem to alleviate the problem. Apparently the gases continued to flow from the landfill beneath the trench into the farm field.

In the spring of 1972 soil tests were made in the areas of the farm where vegetation was undamaged and where the vegetation had been killed by the landfill gases. The nutrient quality of both soil areas was found to be the same. In March 1973 the landfill operator installed 4-inch plastic vertical venting pipes along the total length of the landfill-farm field interface. These pipes were put in to a depth of 30 to 40 feet on 20-to 25-foot centers.

In April 1973 the farmer and the landfill operator developed an interim agreement relative to payments for damages claimed by the farmer and corrective actions to be taken by the landfill to alleviate the gas problem. In December 1974 the farmer noted areas farther from the field where his rye cover crop was dying (fig. 3). A check of the ground gases in these areas revealed the presence of combustible gases up to 600 feet from the nearest edge of the landfill. In summer of 1975, combustible gases were found more than 750 feet from the nearest edge of the landfill. At this time they were damaging commercial corn and sweet potato crops. It appears that the venting pipes were not functioning properly; although visual examination indicated that ground gases are being vented to the atmosphere by the pipes. Suggestions made

Figure 3.—Rye planting in farm field adversely affected by landfill gases 600 feet from nearest edge of the landfill at Cinnaminson, N. J.



to improve gas-venting include installing pumps on the pipes to withdraw the combustible gases from the landfill and venting from greater depths.

As indicated above, we found landfill gases 180 feet from the landfill in the spring of 1971, 300 feet from the landfill in the fall of 1971, 600 feet from the landfill in December 1974, and 750 feet this summer (1975). However, the migration of these gases has not been constant. Measurements taken at a number of other times indicated that the gases had apparently retreated toward the landfill. Their outward movement seems to be at an uneven rate, depending upon various factors, many of which are not understood. Incidentally, the consultant hired by the landfill company reported that the degree of migrating gases has decreased with time. Obviously our data conflicts with his. Some of this disagreement might be due to making measurements at different locations and times.

We will continue to follow this situation and determine the ultimate fate of the landfill gases and vegetation growth in the fields. Eight to 10 acres of the farm field are now involved in problems of poor or no vegetation due to the adverse influence of gases from the landfill located to the north of the field.

The landfilling directly north of Union Landing Road is nearly complete. Completion of the landfill will involve filling the westerly corner of this former sand and gravel pit. This additional filling will bring the refuse in contact with the soil along Union Landing Road for an additional few hundred feet immediately opposite the Hunter Farm. This includes an area on which a farmhouse is located plus an additional few hundred feet immediately opposite the Hunter Farm commercial farm fields. It is possible that the refuse will be located against a soil bank within about 100 feet of the farmhouse.

This farmhouse has a dirt-floor cellar, which is used to store various farm crops during the winter. Therefore we have set up permanent gas-sampling stations opposite the landfill area still to be filled. In addition to exposing this farmhouse to possible infiltration of landfill gases, another private home and at least one light-industry building will also be within a couple of hundred feet of the refuse upon completion of the landfill. Unless adequate protective measures, such as a gas barrier or adequate vents or both, are taken to prevent the movement of landfill gases, it is possible that these buildings and additional farm fields will in time become involved with the combustible gases travelling underground from the landfill.

GAS MEASUREMENTS

All our underground gas measurements were made by adapting various gas-measuring equipment that was originally designed for making safety checks and measuring combustion efficiencies. To determine whether or not foreign gases are present in the soil atmospheres, it is necessary in most cases to first make a hole in the ground. Currently we are using a commercial bar hole maker to obtain a 3-foot deep, ½-inch hole. This commercial instrument (fig. 4) incorporates a steel hole-making rod and driving weight in one convenient unit. This same type of unit is used by most gas utility companies when searching for leaks from their underground pipelines. The handle of our hole maker is electrically insulated to prevent a shock should it come in contact with a live underground electric wire.

The sample is withdrawn from the bar hole by use of a 3-foot long nonsparking probe. If desired, a nonconducting probe may be used. A rubber stopper is placed over the upper end of the sampling probe to help seal the bar hole from the ambient air. However, the nature of the sampling method frequently allows large quantities of ambient air to dilute the sample.

Figure 4.—Bar hole maker is held by man on left. Right, reading an MSA Explosimeter to measure the concentration of combustible gases in a sample drawn from the bar hole.



The most convenient test for checking for the gases of anaerobic decomposition of organic matter is with a combustible gas meter. We pass our gas sample, which is drawn from the bar hole, through an M.S.A. Explosimeter, an instrument used by the gas utility companies when checking for leaks in their underground lines. The Wheatstone bridge principle is used in the instrument for determining gas concentration. The combustible gases are burned on a heated catalytic filament, thereby changing its resistance. This unbalances the bridge, giving a reading on the galvanometer.

These combustible gas-measuring instrument readings indicate the percentage of the lower explosive limit of the gases for which the instrument is calibrated. The lower explosive limit for methane is a 5-percent dilution in air. However, it is possible to tell from the response of the meter whether or not the combustible gas concentration is between the lower and upper explosive limits or above the upper explosive limit (15 percent methane in air). By use of a dilution tube on the intake side of the meter, it is possible to theoretically determine the actual combustible gas concentrations up to 100 percent methane. It is also possible to separate heavy petroleum vapors from the lighter hydrocarbon gases by use of an activated charcoal filter on the sampling line. Regular calibration is required.

The carbon dioxide and oxygen concentrations of the ground gases obtained from the bar holes are analyzed by the Orsat method, normally used to measure the efficiency of fossil-fuel-fired furnaces. In our field-test work we use the Bacharach Fyrite carbon dioxide and oxygen indicators. In the carbon dioxide indicator, the CO_2 is absorbed in a potassium hydroxide solution. In the oxygen indicator, a chromous chloride solution is used. Carbon dioxide indicators are available for reading 0 to 20 percent and the 0 to 60 percent concentrations. The oxygen indicators are for determining 0 to 21 percent concentrations.

Unpleasant ground gas odors are frequently an indication of gases of anaerobic decomposition of organic matter. These unpleasant odors can often be checked for by withdrawing a soil sample from the ground and smelling the sample.

We have occasionally used industrial hygiene dry-tube indicators to check for the possible presence of sulfur gases and carbon monoxide. However, in general we find the field test for combustible gases to be the easiest, quickest, and simplest to make. Our next most frequently used field check is for carbon dioxide. Normally we would not expect to record the presence of combustible gases or carbon dioxide with these field-test meters if there were not significant quantities of the gaseous products of anaerobic decomposition present in the soil gases.

Characterization of Biological Particulate Loads in Metropolitan Air

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ABSTRACT.—The atmospheric particulate load includes a wide range of naturally occurring particles of biological origin that serve as a reservoir of allergenic agents in respiratory disease. Improved knowledge of potential aeroallergens is needed by medical clinicians. Aims are to better characterize air spora, qualitatively and quantitatively, and determine daily (by hour) periodicities of occurrence and prevalence of different kinds of spores, and seasonal variations. Main emphasis is on fungus spores about which least is known though they occur in considerable numbers. Efficient volumetric samplers provide time-related deposits of air spora at three sites in Pennsylvania.

INCLUDED IN THE ATMOSPHERIC load of particulates is a wide range of naturally occurring particles of biological origin, such as microorganisms, pollens and other plant spores, fragments of plants and insect parts, etc. This diverse air spora of natural origin also serves as a reservoir of allergenic agents in respiratory disease. Improved knowledge of potential aeroallergens is much needed by medical clinicians.

Characterization of airborne biological particulates is the first phase of a study of aeroallergens being carried out at the Center for Air Environment Studies at The Pennsylvania State University. Aeroallergens are defined as substances encountered in the air which can incite allergic responses. Generally, these are inhalant allergens, and the major responses are allergic rhinitis, including seasonal hay fever, and bronchial asthma.

Primary aims of this phase of the project are to apply modern techniques of air spora study to: (1) characterize qualitatively the potential aeroallergens, mainly fungus spores and pollens, of major regions of Pennsylvania; (2) to provide quantitative volumetric data on air spora; and (3) to determine circadian (daily, time-related) and seasonal periodicity of occurrence and prevalence of different kinds of spores. We also are beginning to relate spore data to appropriate meteorological variables where possible.

The economic impact of aeroallergens can be assessed in only general terms. Of the United States population, about 15 percent may be sensitized easily to many allergenic materials and another 25-30 percent are considered somewhat sensitive *(Kern 1962)*. Approximately 15 million persons in the U.S. suffer effects of hay fever and/or asthma. More than $70 million are spent on prescription medications related to allergic response each year. About 25 million work days are lost per year due to hay fever. Further, lowered work efficiency due to symptoms and sedative effects of some medications is probable. Allergic rhinitis also often increases susceptibility to infections of the respiratory tract. Asthma incidence leads to an estimated $260 million a year in resource costs, including premature deaths, medical treatments and absenteeism *(Finkelstein 1969)*.

Almost any organic material, from plant or animal sources, may be a po-

tential allergen. Among the more common known aeroallergens are pollens, fungus spores, danders (animal hairs, feathers, flakes of epidermis, etc.); house dust (heterogenous mixture); insect parts; algae; certain cosmetics; and products containing linseed oil, organic solvents, etc.

The two most important groups of naturally occurring aeroallergens are the pollens and fungus spores. Pollens are usually considered to cause the most problems, and ragweed is believed to account for some 90 percent of pollenosis in the U.S. *(Hewson 1967)*.

POLLENS IN THE ATMOSPHERE

Pollens are produced in great numbers throughout the world. Of the approximately 100,000 known species of flowering plants, about 10 percent are adapted to wind pollination *(Gregory 1973)*. Most pollen grains range in size from 15 to 50 μm, and most species have distinctive features and characteristic size. Gravitational fall rates range from about 1 to 10 cm/sec. In general in the temperature zone, the tree-pollen season is in the spring, the grass season from late spring through summer, and the weed season mostly in late summer and fall. There are of course variations and overlappings depending on species and climate as well as more local meteorological conditions.

The members of the ragweed group *(Ambrosia* sp.*)* are prolific pollen producers, and the pollen grains are exceptionally well suited to aerial dissemination. The plants may grow in abundance where soil and cover vegetation have been disturbed as in housing developments, along highways, railroads, etc., as well as on agricultural land.

Millions of acres in the U.S. are infested by ragweeds to some extent. Surveys have revealed as many as 170,000 plants/acre (about 42/m^2) in some fields when no cover crops were grown after winter cereal grains were harvested. About 56,000 plants/acre (11/m^2) were found in a subdivision area under construction *(Hewson 1967)*. An estimated 50 pounds (22 kg) of pollen could be produced by an acre of giant ragweed plants in a season *(Finkelstein 1969)*; at 200 million grains/gram of pollen, this means 4.5 x 10^{12} pollen grains could be produced per acre over an 8-week pollen production period. About 5 to 10 percent of the pollen can be expected to become airborne.

The distance traveled depends on many factors, and it should be noted that airborne particles are being deposited continuously on surfaces near the ground. Despite deposition, the proportion escaping to be transported some distance from the source places considerable numbers in the air to be dispersed over large areas. Concentrations of several hundred ragweed pollen grains/m^3 of air are not uncommon over much of the central and eastern U.S. during the ragweed season each year *(Hewson 1967)*. Peak concentrations over cities some distance from major sources may reach several hundred per m^3 in some areas. Cities often have local sources of ragweed as well.

The relationship of concentration of pollen in the air to production of symptoms is not well known. Individuals may differ greatly in their sensitivity to dosage. However, it has been reported that as few as 100 pollen grains inhaled over a 1-hour period often caused symptoms, and in one individual as few as 30 incited hay fever *(Connell 1968)*. Since the volume of air inhaled approximates 1 m^3/hr for an adult engaged in light activity, it is apparent that exposure levels commonly encountered could readily incite allergic responses in susceptible individuals. It is also known that being sensitized to one pollen or substance can increase sensitivity to certain other allergens *(Connell 1969)*.

Ragweed pollen fall rate in air due to gravity is about 1cm/sec, thus convec-

tion currents can readily carry them aloft. Most ragweed pollen is released in the morning hours, but concentration peaks may occur also later in the day or at night due to pollen descending from high altitudes. In general there is a decrease in concentration with height, though greater numbers may occur at 1 or 2 km altitude than at ground level, due to various atmospheric factors and source locations *(Gregory 1973)*.

FUNGI IN THE ATMOSPHERE

Fungus spores, which are usually more prevalent in air than pollens (often >75 to 1) also can act as potent allergens *(Hamilton 1959)*. Fungi grow on organic matter and some parasitize living plants, insects, and animals. Most spores occurring commonly in outside air originate from fungi growing on plant debris or on surfaces of living plants, trees, etc., rather than from soil as sometimes inferred. Air in buildings may in addition to spores from outside air also contain spores from moldy surfaces and mildewed materials within the building.

Fungus spores are usually smaller than pollens. Most range in size from 3 to 30 μm (the size range of water droplets in clouds). Gravitational settling rates are 0.05-2 cm/sec, and thus most fungus spores become airborne and remain suspended longer than pollens. Viable fungi have been recovered at altitudes of 17 miles (27 km), and over oceans thousands of miles from land as well as over the North Pole *(Ingold 1971)*.

Many thousands of species of fungi produce spores that may become airborne. (Fortunately only a few hundred types are found in air samples that we have studied!) A few examples of prolific spore production are as follows: a single large puffball may contain 7×10^{12} spores; a large specimen of bracket fungus may produce 3×10^{10} spores/day for a 5-month season; an average field mushroom might produce 10^8 spores per day; a single smut-diseased wheat grain may contain 12×10^6 spores; and a single colony of blue mold *(Penicillium* sp.*)* 2.5 cm (1 in) diameter may bear about 4×10^8 spores *(Ingold 1971)*.

Concentrations of about 10,000 fungus spores/m^3 of air may be typical on a summer afternoon *(Hirst and Hurst 1967)*. Numbers may vary greatly, depending on species prevalent, previous conditions for growth and spore production, location, climate, geography, season, weather (temperature, humidity, wind speed, turbulence, etc.), time of day, biotic factors, etc. Exposure depends on an individual's activity and location at any particular time.

Spores of the genus *Cladosporium (Hormodendrum)* seem to be the most numerous found in samples from several places in the world, often comprising about 50 percent of the total spores recorded. This genus is also considered one of the more allergenic encountered.

SAMPLING SYSTEMS

The practice of allergic medicine in the United States has, to some extent, been dependent upon an incomplete knowledge of the kinds and amounts of spores in the atmosphere, particularly fungal spores. This project aims at providing improved characterization, qualitative and quantitative, of air spora occurrence. The main emphasis is on fungus spores, since pollens are better known *(Wodehouse 1971, Jones 1952, Hyde 1959, Hyde and Adams 1958)*, and the modern techniques of air-spora study employed are well suited to improved sampling of the smaller fungus spores. Also, excellent studies of ragweed pollen production and dispersal have been undertaken *(Sheldon and Hewson 1962, Ogdon et al. 1966 and 1969, Harrington 1965, Raynor et al. 1973 and 1974)*.

In 1946, the American Academy of Allergy standardized the methods of assessing pollen in the air *(Durham 1946, Durham et al. 1947)*. This "gravity set-

tling" method was extended to estimates of fungus spores in 1948 *(Merksamer and Sherman 1958)*. In prior surveys, culture-plate studies were made. Much useful information has been derived from these methods, and they are still in common use.

After the development and testing of efficient volumetric suction samplers *(May 1945, Hirst 1952, Andersen 1958)* it became quite clear that the simple gravity samplers can give very distorted estimates of pollen and fungus spore concentrations and may result in serious underestimation of the number of different types actually present in the air. Problems are more serious for fungus spores than for most pollens, and this is particularly true for species producing smaller spores *(Gregory 1952, Gregory and Hirst 1957, Ogden and Raynor 1960, Solomon 1970, Ingold 1971)*.

In the last 20 years a great deal has been learned about circadian and seasonal periodicities of several fungus spores and pollens, especially in England, and in some studies in the U.S. The techniques of volumetric sampling, coupled with time discrimination of deposits, showed clearly that a considerable variation often occurs from hour to hour, between night and day, as well as seasonally *(Hirst 1953; Pady et al. 1962, 1967, 1969; Gregory 1952* and *1973; Ingold 1971; Haard and Kramer 1970)*.

RATIONALE

There is little definitive quantitative information concerning fungal aeroallergens for most of North America and essentially none for Pennsylvania. It is to be expected that several other fungi will be shown to be quite prevalent in most areas when systematic volumetric sampling is done *(Gregory and Hirst 1957, Hamilton 1959, Adams 1964, Sayer et al. 1969)*. Further, we do not have qualitative or quantitative comparisons of fungal air spora for different regions as affected by climate, seasons, vegetation sources, etc.

A result of the general state of knowledge is that allergists are in a poor position to relate observed symptoms to known botanical events, and must rely mostly on sensitivity testing with prepared extracts of a limited number of empirically determined allergenic materials. Improved methods of characterizing the air spora will reveal more organisms that should be tested as potential allergens, and may elucidate the causes of some of the seasonal and perennial allergies whose etiologies are still unknown *(Greenburg et al. 1966, Girsh et al. 1967, Paulus and Smith 1967)*.

PROCEDURE

Volumetric samplers are operated at such heights above ground (about 30 m) to determine the general concentrations of air spora. Many if not most of the spores moving over a city have exogenous origins some distance away *(Harrington 1965, Ogden et al. 1966, Freedman 1967, Davies 1969b)*. By situating samplers well above ground level (to avoid obstructions to free air movement, such as nearby buildings, tall trees, etc.), local site effects are minimized. Bias due to very localized sources of spora from within a city is reduced by allowing vertical and horizontal mixing time before reaching the sampler. Thus each sampling station becomes representative of a considerably larger area *(Davies 1969a)*.

The Hirst *(1952)* spore trap is a volumetric suction-impaction sampler that gives continuous and time-related particle deposits from known volumes of air. The Casella model (C. F. Casella & Co., Ltd., London, England) is a 24-hour sampler utilizing a standard microscope slide. The Burkard model (Burkard Manufacturing Co., Ltd., Herts, England) operates continuously for 7 days, using a plastic tape on a revolving drum as the collection surface. Both models draw air at 10 liters/

minute through a 2x14-mm orifice. Particles impact on the silicone-greased collection surface, which moves continuously at 2 mm/hr.

Counts and identification are made by microscope at about 1,000 magnifications at positions corresponding to 2-hour intervals. Data derived show the kinds and number of air spora present (per m^3 of air) and the times of occurrence throughout each day.

Weather data are being obtained from stations near the sampling sites for correlation with air spora data. Meteorological information includes temperature, precipitation, wind speed and direction, and relative humidity. Information on large-scale weather systems or other meteorological data available may also be useful in characterizing patterns of occurrence of air spora as related to changing environmental conditions.

The three sampling stations, started in mid-1972 and currently operating are at: (1) Pittsburgh, atop the 11-story Veterans Administration Hospital in Oakland; (2) Philadelphia, on the roof of a 12-story building in Jenkintown; and (3) State College, at the Pennsylvania State University campus on the top of the press box at the football stadium. They are located to provide data representative of three different regions and climatological zones *(Dailey 1971, Dethier and Vittum 1963)* and should provide information typical of large portions of the state, as well as comparisons of two urban settings and a rural setting. Additional sites may be sampled in the future for more direct comparisons of air spora and clinical observations in close cooperation with allerists.

SIGNIFICANCE

Improved knowledge of air spora is needed by medical clinicians. Prospects are good for correlating clinical observations with types, concentrations, and variations in air spora. A better understanding of what is in the air, and when, will give allergists important leads for selecting allergenic materials and extracts for testing and treatment. Fungal spores are ubiquitous and the most common biological component of the atmosphere in most areas. Their importance may well be underestimated in general, particularly those that occur in great numbers but have seldom been revealed by methods commonly in use. Knowledge of circadian periodicities of air spora can be important in determining times of day and peak concentrations of aeroallergens to which patients may be exposed. It seems likely that large populations can be included within the zones applicable to the selected sampling sites and representative of the areas, particularly the regions surrounding the large urban centers.

RESULTS

A great number of different kinds of spores are observed in most samples. Many can be identified readily, and separate counts are made of several generally considered allergenic, such as *Cladosporium, Alternaria, Helminthosporium,* and *Epicoccum.* Special note is made of others when they occur in relatively greater numbers than usual.

Counts are routinely made by using a microscope at about 1,000 magnification to ensure seeing the smallest spores, which can be missed at lower powers. This high magnification, though more time-consuming, allows less chance of misidentifications, especially of the smaller and colorless types, which often are seen in great numbers. To set some reasonable limit on the time involved in reading samples, other spores are placed in categories as to type and appearance. These groups are basidiospores, either colored or hyaline, ascospores (two or three types), Penicillium-Aspergillus types, etc. Separate counts are kept of ragweed pollens, which occur for approximately 2 months in the fall, and a total count for other pollens. Total in-

sect parts and other plant parts are also routinely counted. Special notice is made of unusual occurrences of types not usually seen, or normally of low frequency, for possible correlations with clinical data at a later time. The sample slides are essentially permanent and can be reexamined when desired for more detailed or special studies.

Cladosporium

The most consistent and generally numerous type of fungus spores found are of the genus *Cladosporium*. This fungus, in the medical literature often referred to as *Hormodendrum*, has long been recognized as allergenic. The spores are usually released during drying conditions, that is, during the period of lowering relative humidity and increasing air turbulence such as found in the mornings of sunny days. High counts of this group may also occur at other times, even at night, as a result of gravitational settling or the subsidence of air from higher altitudes containing heavy spore loads derived from air that rose earlier in the day, or even on previous days, many miles upwind. Figure 1 illustrates typical occurrences of *Cladosporium* to be expected.

Basidiospores

Most of these spores come from the more commonly seen fungi, due to their larger size, such as mushrooms, bracket fungi, and puffballs. Some basidiospores are released throughout the day as long as sufficient moisture is available to the fruiting structures. Others apparently are released mainly at night when humidity is usually the highest. As a result, peaks of basidiospores in the atmosphere are usually observed between midnight and 0600 hours. It should be noted that because of their small size (mostly 10 μm or less), basidiospores have not often been seen or counted by using the old standard gravity slide techniques. Only with volumetric sampling are we able to provide data as shown in figure 1. The common occurrence of basidiospores in considerable numbers, at times the most prevalent spore group in the atmosphere, has not been generally known to allergists. A need for more clinical testing for sensitivity to members of this group of fungi seems warranted.

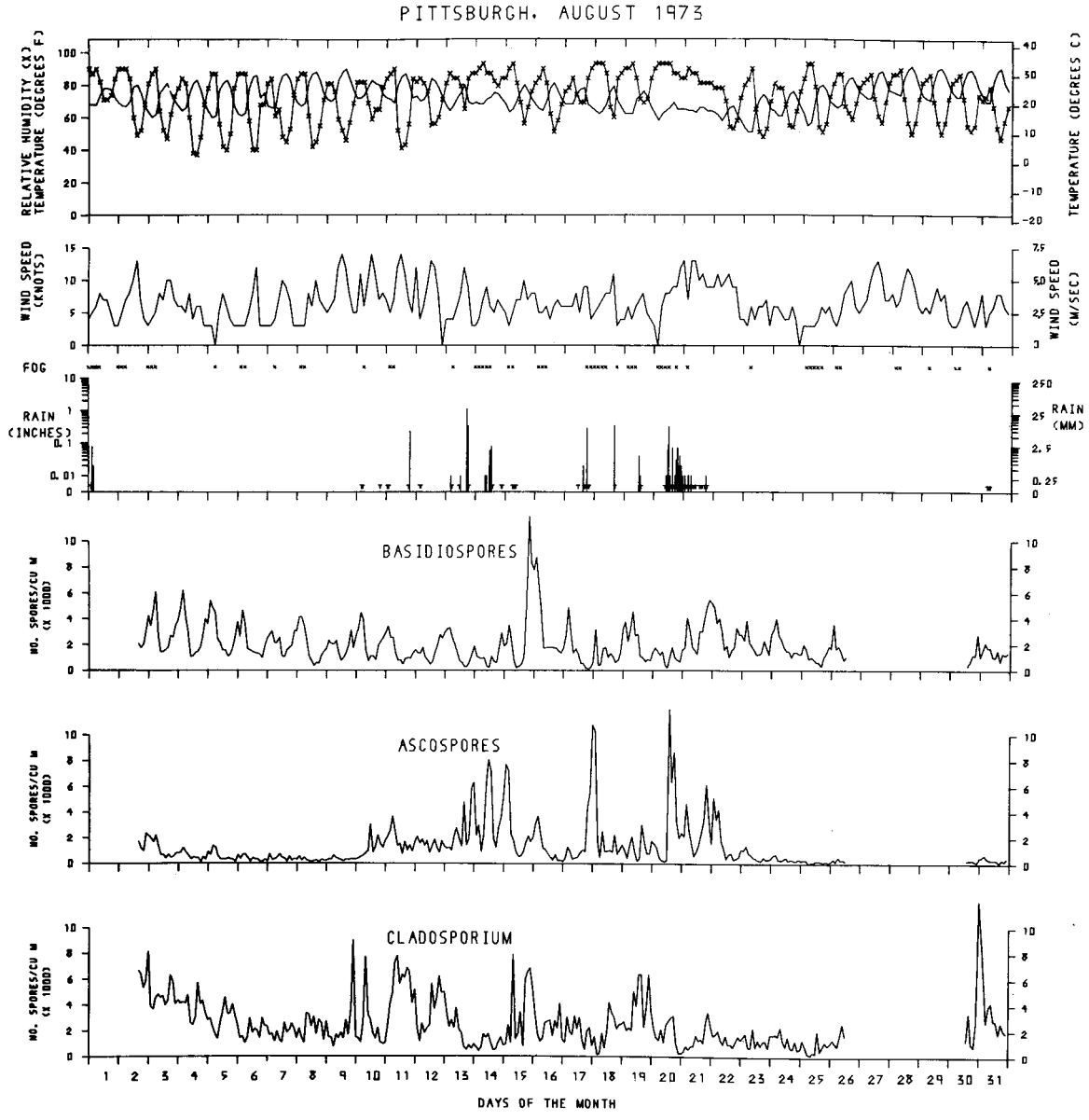
Ascospores

These are the spores from another major group of the fungi, the Ascomycetes. Characteristically, spore release in this large group is dependent upon moisture, and therefore counts are usually highest at night. Following periods of dry weather there may be tremendous increases in spore release shortly after rain. This is well illustrated by our data for 10 and 11 August (fig. 1), where immediately after very small amounts of rain as recorded by the Pittsburgh weather station, the number of ascospores collected increased immensely. Ascospores are considerably smaller than most pollens and often have not been found in such numbers in earlier studies. Because of the high numbers of ascospores sometimes encountered, it seems likely that allergies may be incited by at least some of these. It may be that certain cases of known sensitivity to other spore types, such as *Phoma or Fusarium*, may also be incited by the ascospore stages of these fungi that may more readily enter the atmosphere in outdoor air.

Other Fungi

Many other fungi occur regularly, or occasionally, in variable numbers. Some that have long been known as allergens, such as *Alternaria* and *Helminthosporium* types, occur fairly regularly but in much lower concentrations compared to the above-mentioned types. This does not necessarily mean they are less important than assumed as aeroallergens, since they may have potent antigens and thus require few spores to produce allergies. It does, however, seem to em-

Figure 1.—Fungus spore concentrations at 2-hour intervals, from Pittsburgh air samples, August 1973.



phasize the potential importance of spore types usually occurring in much greater numbers but which have not been known or tested clinically.

Miscellaneous Biological Particulates

Several other biological particles are seen in samples, usually in relatively low numbers, such as insect scales, algae, plant hairs, lichen fragments, and moss and fern spores. Their importance as potential aeroallergens has not been fully assessed.

Pollens

Even though the data presented were collected during the usual ragweed season, the numbers of pollens were low

compared to the fungus spores present. During August (fig. 1) the daily average concentration of ragweed pollen was 53/m³, ranging from 2/m³ on 3 August to 250/m³ on 30 August; and in general increasing throughout the month. Average concentrations for the first half of the month were 22/m³, and for the second half, 85/m³. Peak hourly concentrations ranged from about 25/m³, occurring on 3 to 7 August, to about 600/m³ at 1100 hours on 31 August. That was also the peak recorded for the season in Pittsburgh, although ragweed pollens persisted in low numbers well into October.

Few other pollens were seen during August. One type, probably from the nettle plant, reached about 200/m³ on 11 August. This type is small for pollen (15 μm) and has probably been underestimated on gravity samplers. It has been reported as allergenic.

General

As would be expected, the air spora are most prevalent during the warmer months. Fewer occur in winter, but concentrations of several hundred fungus spores per m³ of air are not uncommon.

It is clear from the data thus far studied that there occurs a tremendous variation in types and numbers of pollens and fungus spores in the atmosphere, from day to day and hour to hour, as well as seasonally at all sites sampled. The circadian periodicities are evident (fig. 1) as the cyclic variations that occur approximately every 24 hours much of the time.

DISCUSSION

Most previous studies of aeroallergens have depended upon sampling methods, the result of which correlate very imperfectly with the true spore content of the atmosphere, both qualitatively and quantitatively. More reliable assessments are needed. In addition, most previous methods could not provide data on variations in air spora occurring throughout a 24-hour period. Such information could have an important impact on determination and control of allergic diseases.

Improved characterization of the biological particulates in the atmosphere should be of considerable use to allergists. Prospects are good for correlating clinical observations with types, concentrations, and variations of air spora. It is expected that new associations will be evident in the etiology of asthmas and epidemiology of seasonal allergic rhinitis when certain spores are found in previously unrealized high concentrations. Knowledge of circadian periodicities can be important in determining times of day and peak concentrations of aeroallergens to which patients might be exposed. Data accumulated will also be tested for possible correlations with climatic and meteorological parameters. These and other studies in cooperation with allergists will constitute the second phase of this study of aeroallergens and their impact on the susceptible population.

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Acknowledgments. This project is supported in part by Grant No. AI 11256, awarded by the National Institute of Allergy and Infectious Disease of NIH, PHS, HEW. Initial equipment funds were granted by the Pennsylvania Allergy Association, and support was provided by the Center for Air Environment Studies, The Pennsylvania State University (CAES Publication 412-75). We gratefully acknowledge the time generously given by collaborators in supervising the outlying sampling stations: Jay Spiegelman, M.D., and Charles Blumstein, M.D. in Jenkintown; and Leo Criep, M.D., and John Coharchic, chief technician, in Pittsburgh. Thanks are also given for technical assistance in counting air spora to Robert Szymusiak and Christine Winters, and to Claire Martin and Paul Strother for computer programming and graphics development.

Retention of Particulate Lead on Foliage and Twigs of a White Pine Windbreak

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ABSTRACT.—The removal of particulate lead from the air by a roadside windbreak of white pine containing 8 rows of 25-year-old trees and 27 m in depth was studied. Knowledge of particulate trapping and retention was gained by atomic absorption spectrophotometry of the lead burden of foliage and twigs of various ages adjacent to and far from the road. The effectiveness of the windbreak was also shown by comparison of the lead content of the soil beneath the windbreak with that of an adjacent open, undisturbed field.

VEGETATION AND SOILS adjacent to heavily-traveled roads incur significant deposits of lead from automobile exhaust *(Cannon and Bowles 1962, Motto et al. 1970, Page et al. 1971)*. The lead is associated with chlorine and bromine in particles on or embedded in plant surfaces *(Heichel and Hankin 1972)*. Observations that the lead burden is frequently retained tenaciously by vegetation *(Smith 1972, Heichel and Hankin 1972)* prompted us to speculate that foliage and twigs of roadside coniferous windbreaks might filter particulate lead from the air and reduce its dispersion from the road. The efficacy of a windbreak in removing particulate lead was evaluated by analyses of the lead burden of foliage and twigs of various ages adjacent to and far from the road. Also, we compared the lead content of the soil beneath the windbreak with that of an adjacent open undisturbed field.

MATERIALS AND METHODS

Site

The windbreak of white pine *(Pinus strobus)* trees growing as a dense roadside screen west of the curb of a heavily-traveled two-lane highway in Hamden CT contained 8 rows of 25-year-old trees and was about 12.2 m tall in the center. The near drip-line of the windbreak commenced 3 m from the curb of the highway, and the far drip-line terminated 30.5 m from the curb. Thus the windbreak was about 27 m in depth.

An open field adjacent to the highway and about 150 m north of the windbreak served as a control site for measuring lead accumulation in soil. The field had not been tilled since establishment of the windbreak and supported a lush growth of perennial forage species that was mowed once a year and allowed to decompose.

Table 1.—Daily traffic flow past the windbreak in 1973

Month	Average daily traffic[1]
	No. of vehicles
January	12,960
February	12,960
March	13,680
April	14,500
May	15,600
June	15,800
July	15,000
August	14,700
September	14,800
October	15,100
November	14,400
December	13,200

[1]Source: Connecticut Department of Transportation.

Traffic Flow

Commuter and truck traffic passed the windbreak at 65 to 73 km/hr. A survey station maintained by the Connecticut Department of Transportation 1.6 km north of the windbreak recorded the average daily traffic flow on a monthly basis during 1973 (table 1). Traffic volume during the course of the investigation ranged from 15,800 vehicles/day in June to 13,200 vehicles/day in December, with a mean of 14,800 vehicles/day.

Wind and Precipitation

Records of the prevailing wind patterns in the locality of the windbreak *(Brumbach 1965)* revealed that the trees were downwind of traffic for 3 of the 8 months of the investigation—May, September, and October (table 2).

Precipitation for the 30-day period before each sampling was monitored at the Mt. Carmel weather station located 4.8 km south of the windbreak (table 2).

Sampling and Analysis

Branches were sampled on seven occasions from May to December 1973 from limbs 0.75 to 1.5 m above the soil surface, separated into needles and twigs of various ages, oven-dried, and ground. For measurements of soil lead content, transects were established through the windbreak and across the open field. Samples of the upper 5 mm of needles on the soil beneath the windbreak, and of the upper 20 mm of mineral soil under the windbreak and open field, were oven-dried. Lead analyses were by atomic absorption spectrophotometry *(Fletcher 1971)*.

RESULTS AND DISCUSSION

Knowledge of particulate retention was revealed by the lead burden of needles and twigs adjacent to and far from the road. Needles on the windbreak adjacent to the road persisted 27 months between emergence in late May and senescence 2 years later in September, while needles far from the road persisted 1 month longer.

The lead burden of older needles was consistently greater than that of younger needles (fig. 1 and 2). On 14 June, for example, 1972 needles near the road bore nearly 4-fold and 1971 needles nearly 6-fold the 35 μg/g dry-weight lead burden of 1973 needles. The 1972 needles far from the road bore 3-fold and 1971 needles nearly 6-fold the 5 μg/g lead burden of 1973 needles. Except for the 20 August samples obtained near the road, and the 29 December samples far from the road, older twigs bore a greater lead burden than newer, younger twigs (fig. 1). Clearly, the lead burden of coniferous foliage and twigs was directly related to the duration of exposure to contamination.

The lead burden of needles and twigs varied with time of year (fig. 1 and 2). The burden of 1971 needles sampled

Table 2.—Wind and precipitation in the vicinity of the windbreak

Sampling date (1973)	Mean monthly wind direction	30-day cumulative precipitation at sampling
		(cm)
15 May	East	13.31
14 June	Southwest	9.73
July	Southwest	—
20 August	Southwest	11.71
17 September	Northeast	4.60
30 October	Northeast	8.38
26 November	Northwest	7.34
29 December	Northwest	30.33

Figure 1.—Patterns of retention of lead on needles and twigs located on the near side of a white pine windbreak adjacent to a road.

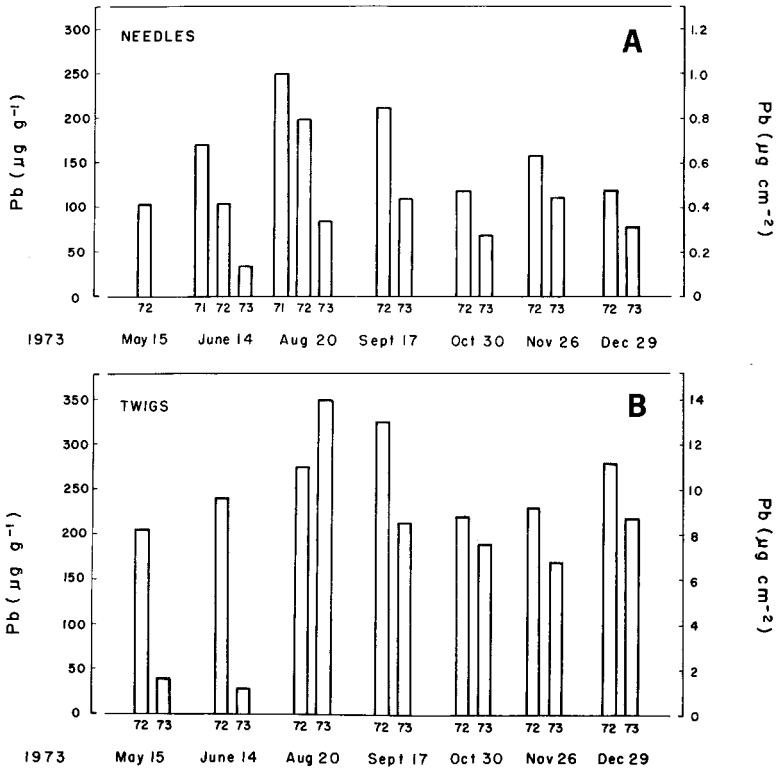
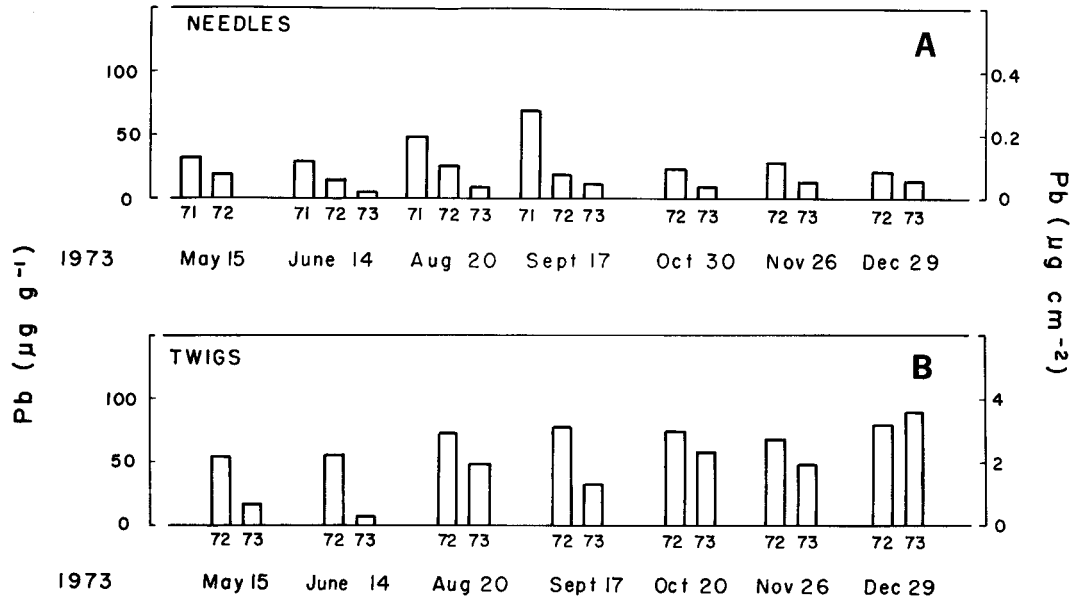


Figure 2.—Patterns of retention of lead on needles and twigs located on the far side of a white pine windbreak adjacent to a road.



near and far from the road increased from May until they were shed in September. The lead content of 1972 and 1973 needles obtained adjacent to the road peaked in September and then declined during the remainder of 1973. In contrast, the lead burden of 1972 and 1973 needles sampled far from the road remained relatively invariant throughout the year (fig. 2A).

The increase in the lead burden of 1972 and 1973 twigs near the road continued until August, commenced to decline about 1 month before that of needles, and then increased slightly in December (fig. 1B). The lead content of 1972 and 1973 twigs far from the road slowly increased throughout the year, in contrast to the pattern of lead accumulation on twigs adjacent to the road (fig. 2B). Adjacent to the road, therefore, the pattern of lead accumulation throughout the year on twigs was similar to that of needles except for a slight shift in phase.

The pattern of lead accumulation on fully expanded needles varied with precipitation in the interval preceding sampling (table 2, fig. 1A). About 4.6 cm of precipitation, 61 percent less than in the previous sampling period, occurred between 20 August and 17 September. Concurrently the lead burden of 1972 foliage increased 2 percent and that of 1973 foliage 29 percent by 17 September compared with 20 August. In contrast, 8.4 cm, or 82 percent more rain fell in the 30 days ending on 30 October, and the lead burden of 1972 and 1973 foliage was diminished about 45 percent compared with that of the 17 September sample. About 7.4 cm of precipitation, or 13 percent less than in the September-October interval, fell in the 30 days ending 26 November. This decrease in precipitation was accompanied by a 32-percent increase in the lead burden of 1972 foliage and 60 percent increase in that of the 1973 foliage on 26 November compared with 30 October.

As a final illustration, 30.3 cm of water fell as rain, sleet, and snow in the 30 days before the 29 December sampling. This abrupt increase in precipitation was accompanied by a decline of 24 percent in the lead burden of 1972 foliage and 30 percent in that of 1973 foliage compared with 26 November. In contrast, the pattern of lead accumulation on twigs was unrelated to the pattern and quantity of precipitation, presumably because particles are less easily dislodged from the rugged topography of twigs than from the waxy, even surfaces of needles.

The seasonality of traffic flow apparently had no effect on the pattern of lead accumulation on foliage and twigs adjacent to the road (table 1, fig. 1A and 2A). Peak traffic flow occurred in May and June, but maximum lead accumulation occurred in September. Traffic flow increased between August and October, but the lead burden of twigs and needles declined. Compared with the changes in lead burden related to precipitation, seasonal traffic-volume changes of 3 to 8 percent were clearly insufficient to be reflected in lead deposition on needles and twigs. Finally, the expected dilution of the lead burden by rapid foliage and twig growth from May through July did not occur. Indeed, lead accumulated rapidly on foliage and twigs at this time of year.

Retention of lead by needles and twigs was evaluated on mass and area bases (fig. 1 and 2). Twigs of various ages near and far from the road retained about 115 percent more lead/g than similarly located needles. We observed, however, that needles displayed about 10-fold more area/g than twigs. Thus, twigs retained about 2,050 percent of the lead burden/cm of similarly located needles. Clearly, the surfaces of twigs retain particles more effectively than the surfaces of needles.

With these retention patterns, the lead burden of a single tree in the windbreak can be illustrated. Unpublished

data of our colleague George Stephens reveals that a 12-m-tall white pine growing in a dense planting would have about 15 x $10^4/cm^2$ of woody surface and about 15 x $10^5/cm^2$ of foliage surface. Although the tree exposed about 10 fold more foliage than woody surface, the woody surfaces retained about 20-fold the lead burden of foliage (fig. 1 and 2). Thus, about two-thirds of the lead on a tree in the windbreak would be retained on the wood, and the remaining third on the needles.

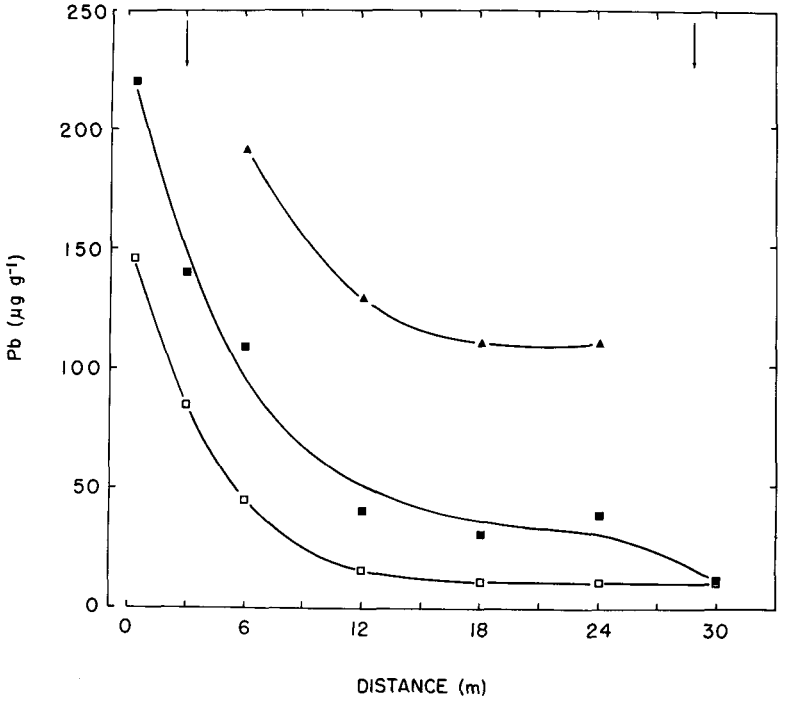
Comparing the soil lead burden beneath the windbreak with that of the open field demonstrated the increased accumulation resulting from the presence of the windbreak (fig. 3).

In the open field, the lead content of the upper 2 cm of soil declined from about 150 μg/g 0.3 m from the curb to 12 μg/g at 18.3 m from the curb, and remained at 12 μg/g to 30.5 m from the curb. However, the soil between the curb and the near drip-line of the windbreak contained 140 to 220 μg/g lead, or about 50 percent more than that of the open field at a similar distance from the road.

Within the windbreak, the soil contained 110 μg/g lead 6 m from the curb to 38 μg/g 24 m from the curb, or about double the lead burden of the field soil at similar distances from the curb. Beyond the far drip-line, the lead burden of the soil near the windbreak, 12 μg/g, was similar to that of the field soil at the same distance from the curb (fig. 3).

Compared with that of the open field, the lead burden of the soil beneath the windbreak might be enhanced by incorporation into soil of needles, twigs, and bark that fall from the trees, by re-

Figure 3.—The lead burden of the needle litter (▲) and soil (■) beneath a windbreak, and of soil in an open field (□) at various distances from a road. The curves are drawn by hand. Distance=0 is the curb, and the arrows indicate the canopy drip-lines.



moval of impacted lead from the surfaces by precipitation, and by increased sedimentation of particles from the air.

That needlefall would enrich the soil with lead was shown by sampling the litter layer beneath the windbreak. The uppermost 5 mm of needles beneath the windbreak was enriched 76 to 300 percent compared with the upper 2 cm of underlying soil. The lead content of the needle litter on the roadward side of the windbreak was about 190 μg/g, similar to that of the 1971 needles that were sampled prior to senescence in early September. The lead burden of the needle litter mirrored that of the underlying soil and diminished with distance into the windbreak (fig. 3). The rates of deposition of lead from twigs and bark in the litter layer remain to be evaluated.

There have been numerous reports that, in the laboratory, washing with water removes lead from leaf surfaces rather easily *(Page et al. 1971, Smith 1972, Little 1972)*. Our field results further illustrate this by revealing that the lead burden of needles, but not of twigs, varies with patterns of precipitation.

Compared with needles, the invariance of lead removal from twigs by precipitation is probably due to the characteristics of woody surfaces. Lead particulates are undoubtedly less easily eroded from the fissures, cracks, and seams of woody surfaces than from comparatively smooth needle surfaces.

The pattern of wind movement into and through windbreaks might be of substantial significance in the deposition of lead-bearing particulates. For a windbreak having a composition and dimensions similar to ours, Caborn *(1957)* showed that the wind velocity on the leading edge was reduced to about 70 percent of the free wind velocity. That sedimentation of particles from moving aerosols increases with diminishing wind speed is well established *(Davies 1966)*. Moreover, 30 to 50 percent of the particulate lead in automobile exhaust is larger than 5 μm diameter *(Hirshler and Gilbert 1964)*, has settling velocities greater than 0.3 cm/sec, and likely settles more rapidly within the windbreak than without.

Compared with the open field, therefore, reduction of wind velocity at the roadward edge of the windbreak might account for a significant proportion of the increased lead burden in the soil adjacent to the road. Additionally, eddy circulation on the leading edge of a relatively impenetrable windbreak is groundward *(Caborn 1957)*, and this pattern of air movement might enhance deposition of particulates on the soil surface.

Within a windbreak having a structure similar to ours, Caborn *(1957)* observed that the windspeed was only 50 to 60 percent of the free wind velocity. A halving of windspeed might be expected to double the rate of particulate sedimentation from moving aerosols *(Davies 1966)* like automobile exhaust dispersing from roadways. Our observations that the soil within the windbreak bore about double the lead burden of that of the open field therefore conform to expectation.

Windbreaks have long been used to shelter plants from the desiccation of brisk and persistent winds. Our results, however, suggest another role for windbreaks in the urban environment: to act as a sink for particulate pollutants and thereby beneficially modify their dispersion from roadways.

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Acknowledgment. We thank Richard Botsford, Analytical Chemistry Department, The Connecticut Agricultural Experiment Station, for the atomic absorption spectrophotometry, and Richard Mangan for technical assistance.

A Model for Estimating Air-pollutant Uptake by Forests : Calculation of Absorption of Sulfur Dioxide from Dispersed Sources

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ABSTRACT.—The computer model presented in this paper is designed to estimate the uptake of air pollutants by forests. The model utilizes submodels to describe atmospheric diffusion immediately above and within the canopy, and into the sink areas within or on the trees. The program implementing the model is general and can be used with only minor changes for any gaseous pollutant. To illustrate the utility of the model, estimates are made of the sink strength of forests for sulfur dioxide. The results agree with experimentally derived estimates of sulfur dioxide uptake in crops and forest trees.

AS DEFINED BY SMITH *(1972)*, there are three levels of interaction between forests and air pollution. The most obvious and most studied interaction is at high pollution levels where there is visible air-pollution damage or mortality of forest trees. At a lower level of pollution concentration there may be no visible damage, but more subtle damage may occur, such as loss of productivity or changes in species composition. Finally at still lower concentrations there may be no damage or possibly even a beneficial effect on the forest. At this lowest concentration level, and perhaps at levels where the damage is small compared to the benefit from pollution abatement, forests can be effectively used as sinks for some types of air pollutants. The effective use of forested green belts around urban and industrial areas depends on absorption at these pollutant concentrations.

The amount of a particular pollutant that will be absorbed by the forest is related to the atmospheric processes and source geometry that affect the delivery of the pollutant to the forest and the type of interaction that takes place between the forest and the pollutant. The simplest source geometry is a dispersed source, which is approximated by many small closely-spaced sources. This arrangement leads to a pollutant concentration near the forest, which varies slowly in time and space. For this kind of geometry, pollutant uptake can be treated as one-dimensional, vertical diffusion with a quasi-steady-state boundary concentration. It is one of the simplest absorption geometries for a forest and is the case dealt with in this paper. More complex cases include absorption under plumes or multiple plumes that have rapidly changing pollutant concentrations in time and space and must be studied by using more complex three-dimensional analyses.

The types of interactions between the forest and a particular pollutant depend on the chemical and physical reactions between the pollutant and forest vegetation and soil. The common gaseous pollutants can be grouped roughly according to their physical and chemical reactions with the forest. Some pol-

lutants are essentially unabsorbed by the vegetation, while other pollutants react with plant and soil surfaces or are metabolized inside the plant at a rate that may maintain a steady-state uptake for fairly long periods of time. Intermediate to these two types of pollutants are the pollutants that react transiently by adjusting to new equilibrium concentrations in the plants or soil when external pollutant levels change.

Sulfur dioxide is an example of a pollutant that is actively metabolized by plants and can have steady-state uptake rates for fairly long periods of time when the atmospheric concentration stays below 7 parts per hundred million by volume (pphmv) *(Martin and Barber 1971)*. Therefore its uptake rate by vegetative surfaces can be calculated by using a steady-state, one-dimensional model when the source of sulfur dioxide is of a dispersed nature.

THE MODEL STRUCTURE

A model designed to provide an estimate of pollutant uptake must describe the response of the vegetation-atmosphere system to the environment as it is related to three types of processes: (1) atmospheric diffusion, (2) diffusion near and inside the absorbing plant, and (3) the physical and chemical processes at the sink on or within the plant. The atmospheric-diffusion processes are the result of turbulent eddies, which are related to the state of the atmosphere and the physical structure of the underlying surface. One-dimensional, steady-state atmospheric diffusion with a sink term is described by the equation:

$$\frac{\partial}{\partial z}\left(K\frac{\partial C_a}{\partial z}\right) + S_c = 0 \qquad [1]$$

where

- K = The turbulent diffusivity for mass transfer.
- C_a = The pollutant concentration (mass/volume) in the air.
- z = Height above the ground.
- S_c = Sink strength at height z.

The sink strength term is often zero for many pollutants in the atmosphere above the stand. Within the vegetative canopy it is the divergence of the absorption by the vegetation with height.

In the vegetative canopy, the turbulent diffusivity is a function of eddy size and the fluctuation velocity with which the eddies move. The eddy size or equivalent mixing length must be no larger than the open space available for rotation in the stand. The largest openings are the spaces between the individual trees. Smaller eddies are generated in the wake of canopy elements such as leaves or branches. The fluctuation velocity, which can be visualized as the speed with which the eddies rotate, is usually assumed to be proportional to the shearing stress at any level in the canopy. The defining equations are *(Cionco 1965, Takeda 1963)*:

$$\tau = \rho K_m \frac{du}{dz} \qquad [2]$$

$$\frac{d\tau}{dz} = \rho C_d \frac{dA}{dz} u^2 \qquad [3]$$

$$K_m = \iota \sqrt{\Gamma \rho} \qquad [4]$$

where

- τ = Shearing stress.
- ρ = Density of air.
- K_m = The turbulent diffusivity for momentum transfer.
- u = Wind speed.
- C_d = Drag coefficient of the canopy surfaces.
- A = The surface area of the canopy.
- ι = The mixing length for momentum transfer.

Equations 2, 3, and 4 can be arranged for a simultaneous integration with height providing values of shearing stress, wind speed, and momentum with height, given a means of determining the mixing length. The procedure presented here used the equation

$$\iota = \iota_c X_s + k \bar{S}_P (1 - X_s) \qquad [5]$$

where

ι_c = Mixing length inside the crown.
X_s = Relative cross-sectional crown area at a particular height.
k = Von Karman's constant ($\simeq$0.35).
$\bar{S}_P$ = The average distance between tree crowns.

The spaces between elements within the crown are small compared to the spaces between crowns at most heights in the stand, and thus the values of mixing length inside the canopy are also small, tending to make the effect of the first term on the right-hand side of equation 5 small compared to the second term.

In the turbulent boundary layer above the canopy and in sections of the canopy where there is little surface area to produce drag, equations 2 through 4 can be greatly simplified. In these regions the shearing stress is approximately constant, and the divergence of shear is nearly zero. The value of the mixing length changes approximately linearly with height from the reference height where the shearing stress becomes constant. The constant of proportionality used in the calculations presented later was von Karman's constant ($\simeq$0.35). In the region of the boundary layer above the stand, this value must be corrected to take into account the effect of buoyancy caused by the exchange of sensible heat at the forest canopy. The correction is calculated by using the equations derived by Businger et al. *(1971)* and Paulson *(1970)* and a value of sensible heat flux determined by a surface energy balance, using the Penman-Monteith formula *(Monteith 1965)*.

The sink strength term in equation 1 is determined by the diffusion into the sink area and the absorption process. The diffusional process near vegetative elements is proportional to the concentration gradient and inversely proportional to the series of diffusional resistances in the flow path. In contrast to atmospheric diffusion, which is dominated by turbulent processes, the diffusion near the sink is largely molecular in nature. For materials like sulfur dioxide, which are absorbed inside the canopy leaves, these relationships are expressed by the equation:

$$S_c = \frac{dA}{dz}\left[\frac{SC_a - C_i}{S(r_a + r_s) + r_i}\right] \qquad [6]$$

where

S = The solubility of sulfur dioxide in the cell water.
C_i = The concentration of sulfur dioxide at the sink.
r_a = The leaf boundary layer resistance.
r_s = The leaf resistance associated with diffusion through the stomata in the leaf epidermis.
r_i = The diffusion resistance associated with the cell walls and the cytoplasm.

The boundary layer resistance is proportional to the square root of the leaf aerodynamic length divided by the wind speed. The stomatal resistance is often a complex function of light intensity, temperature, and water stress. When the water uptake from the roots is not limited by soil-water stress, a reasonable approximation of stomatal response can be calculated from *(Gaastra 1959)*:

$$r_s = a + \frac{b}{I + I'} \qquad [7]$$

where

a,b,I′ = Empirical constants.
I = Light intensity incident on a leaf.

The light intensity incident on a tree leaf will be a function of the angle of incidence of the light, the light intensity above the canopy, the leaf angle, and mutual shading of leaves in the canopy. These are incorporated in the model by using an exponential decay of direct beam and diffuse light with cumulative leaf area into the canopy. This results in estimates of the area in direct beam light and of the intensity of direct beam

and diffuse light at any given height in the canopy. Separate resistances based on sunlight and shade intensities are calculated, and a weighted mean resistance based on the relative area in direct sunlight and shade at a given height in the canopy is used in equation 6.

The internal resistance in equation 6 is associated with diffusion through the liquid cell cytoplasm. The value of this resistance and its variation are difficult to determine. We have made an estimate on the basis of internal diffusion resistances calculated from photosynthesis data. The data used were from a series of experiments on phytotron-grown loblolly pine seedlings *(Gresham 1972)*. The calculation of resistance averaged very close to 20 sec/cm *(Sinclair 1972)*. This value is higher than is often found in other experiments. However, since the objective of this simulation is to evaluate the potential of forests as sinks for sulfur dioxide, we decided to use this value, which gives a conservative estimate of absorption.

The solubility of sulfur dioxide in water is very high; therefore the amount going into solution in the cytoplasm of the leaf cells should be large. The mechanism for sulfur dioxide solubility has two components: a reversible chemical reaction converting the gas to soluble sulfurous acid, and normal gas solubility in a liquid. The total equilibrium solubility is given by the equation

$$S = \frac{1}{S_g} + \frac{-H_c + \sqrt{H_c^2 + 4\,K_s\,C_i/S_g}}{2\,C_i} \qquad [8]$$

where

S_g = The gas solubility (Henry's law) constant.
H_c = The hydrogen ion concentration.
K_s = The equilibrium constant for the sulfur dioxide - sulfurous acid reaction.
C_i = The concentration of sulfur dioxide in the air at the air-liquid interface.

At a temperature of 25°C, the Henry's law constant has a value of 0.0332, and the equilibrium constant is 0.0130 moles/liter *(Johnstone and Leppla 1934)*. The values of both these parameters, which are very temperature-dependent, are given over the temperature range of 0°C to 50°C in Hales and Sutter *(1973)*, who also provide a correction factor that must be used at very low values of atmospheric sulfur dioxide concentration.

The internal sulfur dioxide concentration at the sink site in the absorbing cells is related to the nature of the absorption process. Since sulfur is a metabolite of plants, it is reasonable to believe that at least some part of the absorption process is from the synthesis of organic sulfur compounds. Faller *(1972)* has shown that all of a plant's sulfur requirements can be supplied by foliar absorption of sulfur dioxide. In fact, this will be the preferred source for the aerial organs, given the choice of translocating sulfate compounds from the soil or using sulfur dioxide absorbed from the atmosphere. The level at which this type of reaction becomes saturated can be estimated from experimental data. Martin and Barber *(1971)* have shown that the absorption rate versus atmospheric sulfur dioxide concentration of a narrow hedge is linear up to a concentration of 6.0 parts per hundred million by volume (pphmv) where there is a sharp break above which the absorption rate is constant. Bennett and Hill *(1974)* present data showing that there seems to be no additional metabolic cost, as measured by depressed photosynthetic rate, in barley at atmospheric concentrations of 5 pphmv, but there was a reduction of 2 percent at 10 pphmv. Roberts *(1974)* indicates that a *Pyracantha* seedling can continue steady-state absorption of sulfur dioxide for more than 6 hours at an atmospheric concentration of 100 pphmv.

The conclusion that can be drawn from these studies is that the absorption

mechanism is not saturated below values of 5 pphmv and may be able to remain unsaturated for some species above this level. Since National Ambient Air Quality Standards for the United States are 3 pphmv on a yearly mean and 14 pphmv for the 24-hour average, the absorption by forests will often take place under conditions where the metabolic uptake is not saturated. Under these circumstances it seems reasonable to assume that the concentration at the uptake site approaches zero.

Equations 1 through 8 are the basic relationships needed to model the uptake of sulfur dioxide by forest vegetation. The only additional information is the boundary conditions appropriate to a particular environment.

MODEL IMPLEMENTATION

The equations of the model were coded in the Continuous System Modeling Program (CSMP) developed by IBM *(1972)*. This language was chosen over more general-purpose, higher-level languages like FORTRAN or ALGOL because of the large library of subprograms used for systems simulation that are part of the compiler. The leaf area, crown cross-section, and solubility functions were entered as tables, and a standard linear-interpolation program was used to find the values at the appropriate heights and temperatures in the stand. Integration of equations 1, 2, and 3 was accomplished by using a fixed-step Runge-Kutta routine. Integration was started at the bottom ($z=0$) of the stand with values of sulfur dioxide flux, sulfur dioxide concentration, wind speed, and shearing stress. Integration to the highest point desired provided values of these same variables at the upper boundary. It was arbitrarily decided to set upper boundary conditions of sulfur dioxide concentration and wind speed. The sulfur dioxide concentration and the shearing stress at the bottom of the stand were varied until values were found that produced the desired values of sulfur dioxide concentration and wind speed above the stand.

In addition to the boundary values needed for the integration and the tables of leaf area and tree cross-sectional area, other user-supplied inputs are needed to run the program. The leaf aerodynamic length, the constants of the stomatal function, and the other stand data were estimated from a detailed study carried out in a loblolly pine stand as part of the U.S. International Biological program (*Higgenbotham 1974, Gresham 1972, Murphy et al. 1973*).

An energy balance is calculated for the stand to provide values of sensible heat flux for the calculation of diffusivities for mass transfer in equation 4. Input for the energy balance is the incident solar radiation, the incident terrestrial sky radiation, the air temperature, and air humidity above the stand. Two standard cases have been calculated, using idealized values of the climatic input which closely match the average conditions for the coldest and hottest months of the year at the Savannah River Plant, Aiken, South Carolina. The radiation balance is calculated by using the earth-sun radiation geometry for the 15 January and the 15 July to provide estimates of incoming short-wave radiation. Brunt's equation was used to provide estimates of incoming terrestrial sky radiation (*Sellers 1965, chapters 3 and 4*). The net radiation calculated by this method is partitioned between sensible and latent heat transfer by using the Penman-Monteith equation (*Monteith 1965*). Daily air temperature and dew-point temperature (humidity) vary sinusoidally with lags of 3 hours and 6 hours behind the solar-radiation maximum. Values of the required stand structure and climatic data for the two stand conditions are given in table 1.

Table 1.—Input data

Parameters		January 15	July 15
Stand parameters:			
Leaf area index		6.0	9.9
Aerodynamic leaf length (cm)		0.1	0.1
Constants of stomatal resistance equation	a (sec/cm)	3.4	3.4
	b (sec-ly/cm-min)	0.19	0.19
	I' ly/min	0.003	0.003
Drag coefficient of leaves		0.02	0.02
Climatic parameters:			
Average air temperature (°C)		7.9	27.4
Amplitude air temperature (°C)		6	6
Average dew-point temperature (°C)		2.5	21.8
Amplitude dew point temperature (°C)		2	0.5
Wind speed (cm/sec)		260	175
Day length (hr)		8	12

RESULTS AND DISCUSSION

The results of simulations for 2 days representing climatologically average clear days during January and July at the Savannah River Plant site near Aiken, South Carolina, are illustrated in figures 1 and 2. The diurnal patterns are similar. The uptake of sulfur dioxide is at a minimum in the morning and evening and at a maximum sometime before noon. This is inversely related to the average stomatal resistance of the canopy, demonstrating the large effect of this resistance expressed in equation 6. The diurnal pattern of stomatal resistance is a result of our assumption that the resistance is a function of light intensity.

The effect of temperature on the solubility of sulfur dioxide is demonstrated by the uptake maximum occurring before the minimum stomatal resistance at noon. This is because we have assumed that the maximum temperature lags the maximum solar radiation by 3 hours. The solubility of sulfur dioxide in water is inversely related to temperature; thus the maximum absorption takes place at the coincidence of a low stomatal resistance and a high solubility of sulfur dioxide during the cooler morning period.

These results are further illustrated by figures 3 and 4. Figure 3 shows the instantaneous profiles of wind speed, crown cross-section, and sulfur dioxide concentration at 11:00 am of the diurnal simulation shown in figure 2. Figure 4 shows the same conditions except that the radiation inputs to the model are characteristic of a uniformly cloudy sky. The incident solar radiation was lowered from 1.12 ly/min to 0.42 ly/min. The lower incident radiation results in a higher average stomatal resistance at every height in the canopy, lowering the sulfur dioxide uptake by 27 percent. The lower uptake results in higher sulfur dioxide concentrations in the canopy.

A comparison of the total uptake for the January day, 0.29 kg/ha, and the July day, 0.58 kg/ha, shows the type of annual variation that can be expected. As illustrated in figures 1 and 2, one of the sources of this variation is the shorter day length during January. However, even the instantaneous uptake values are lower in January. This is caused by a lower leaf area in January than in July. Although a lower average stomatal resistance might be expected during the winter because of the lower incident solar radiation, this is not the case because there is more shaded leaf area in the denser summer canopy. The effect of the average stomatal resistance is reflected in the fact that uptake per unit leaf area is greater in the January simulation than the July simulation as shown in table 2.

Thus the diurnal pattern of sulfur

Figure 1.—A simulation of the diurnal pattern of sulfur dioxide uptake, net radiation, temperature, and average stomatal resistance for a clear day characteristic of Aiken, South Carolina, during January.

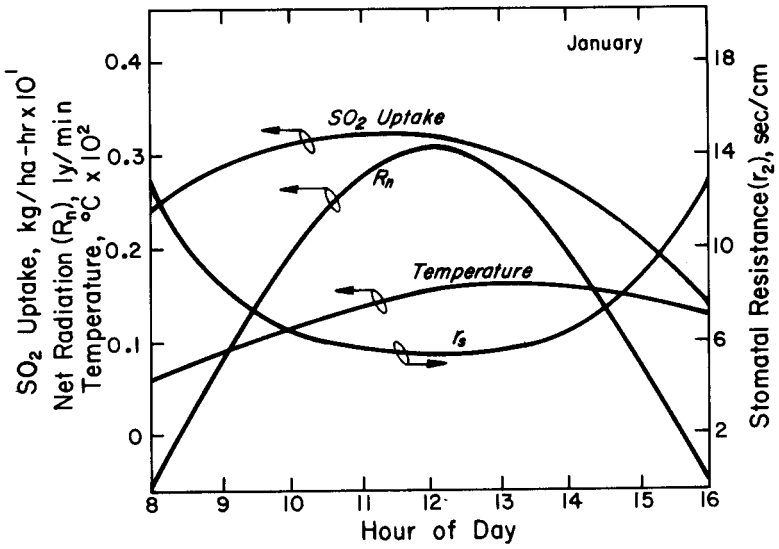
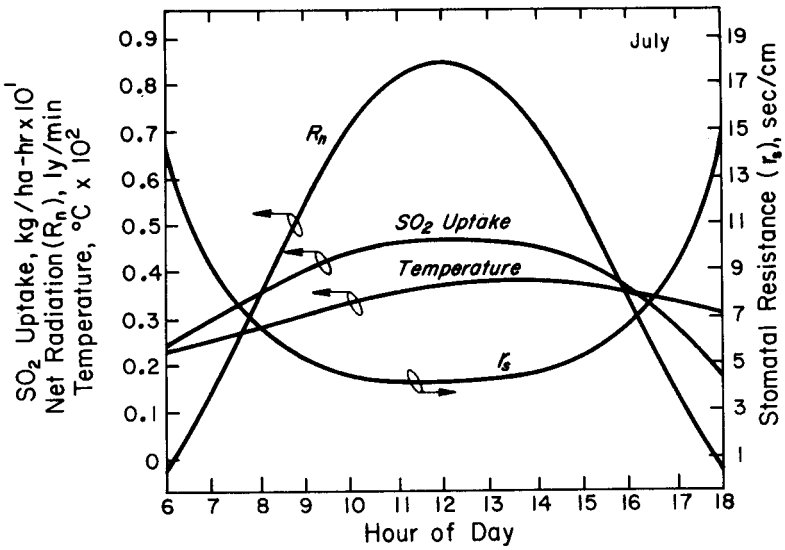


Figure 2.—A simulation of the diurnal pattern of sulfur dioxide uptake, net radiation, temperature, and average stomatal resistance for a clear day characteristic of Aiken, South Carolina, during July.



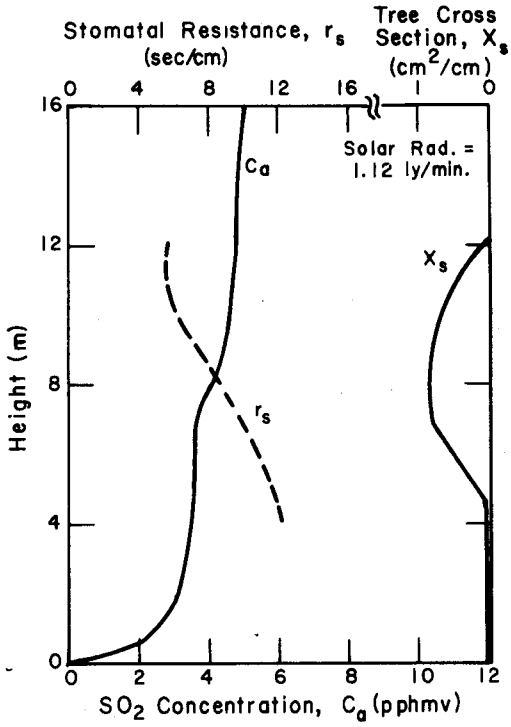


Figure 3.—The distribution of pollution concentration and related tree parameters at high solar radiation.

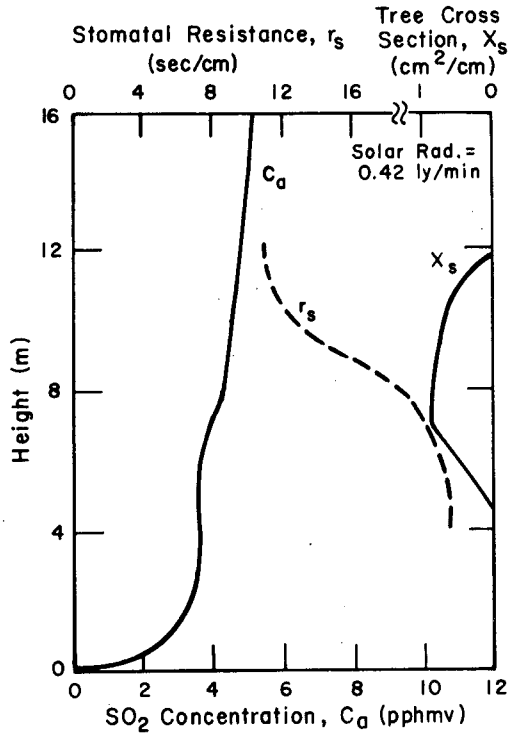


Figure 4.—The distribution of pollution concentration and related tree parameters at low solar radiation.

dioxide uptake reflects the effect of changing solar radiation and temperature on stomatal resistance and sulfur dioxide solubility. The seasonal pattern is affected by these variables and also by the seasonal change in day length and leaf area.

No experimental measurements have been taken under similar climatic and stand conditions, but the uptake rates compare well with those found in laboratory experiments. Table 2 compares the average daily uptake rates from the simulation with the laboratory data of Roberts (*1974*), and Bennett and Hill (*1973*). The results of Bennett and Hill are particularly interesting because an effort was made to duplicate field conditions. The simulated uptake appears to be an order of magnitude smaller than the experimental value. This can be explained on the basis of the high value of the internal diffusion resistance used in the simulation. However, it should be pointed out that the uptake per unit leaf area agrees quite well with the values found for tree species by Roberts, indicating that tree leaves may actually absorb sulfur dioxide more slowly than some other types of vegetation.

Although these results indicate that conifers have a potential for removing sulfur dioxide from the atmosphere, this potential may not be met if climatic conditions are unfavorable. Low light intensity or cold weather can cause stomatal closure and limit sulfur dioxide uptake, as demonstrated in figures 3 and 4. On the other hand, data collected by Martin and Barber (*1971*) clearly show that during periods when atmospheric conditions favor the deposition of dew, this surface water can be a sizable sink for transient absorption of sulfur dioxide.

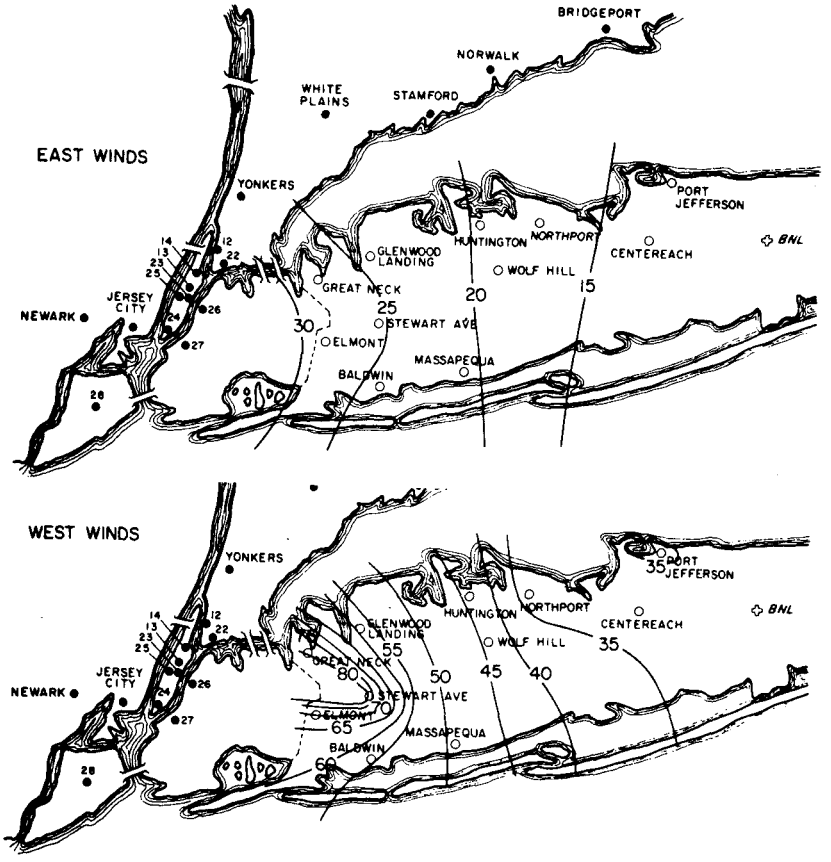
The results of these simulations or similar ones can be used to estimate the uptake of sulfur dioxide over a large area that has trees or crops as a major vegetative component of the landscape.

Table 2.—Comparison of model and experiments

Species	Uptake (kg/ha-hr-pphmv)	Source
Red maple	8.8×10^{-4}	Roberts (1974)
White birch	8.6×10^{-4}	
Sweetgum	7.4×10^{-4}	
White ash	4.6×10^{-4}	
Alfalfa	2.9×10^{-2}*	Bennett and Hill (1973)
	6.2×10^{-3}	
Loblolly pine	7.0×10^{-3}*	January simulation
	1.2×10^{-3}	
	9.8×10^{-3}*	July simulation
	9.8×10^{-4}	

*Based on ground-surface area; other values based on leaf-surface area.

Figure 5.—Mean annual isopleths of sulfur dioxide concentrations with west and east wind over Long Island, New York *(from Raynor et al. 1974).*



This could be forests, parks, farms, or urban areas where the shade trees dominate the surface area. We have made calculations of this type, using the data of Raynor *et al. (1974)* for atmospheric sulfur dioxide concentrations on Long Island, New York (~3276 sq km). Figure 5, redrawn from their paper, shows the average concentrations under two different meteorological conditions. The weighted uptake, assuming the island is completely forested, is 54 metric tons per day for the east-wind case and 256 metric tons per day for the west-wind case, based on the summer values of the simulations shown above.

The sulfur dioxide released to the atmosphere by a large power plant (7,200 metric tons of coal consumed per day) is 280 metric tons per day based on Environmental Protection Agency emission factors (*EPA 1972*). It seems that absorption by vegetation over even large land areas is not significant compared to the output of large power plants. However, if an advanced pollution-abatement method such as catalytic conversion is used, the actual output will be closer to 28 metric tons per day. Under these conditions the forest could absorb a significant portion of the sulfur dioxide present from nine power plants when meteorological conditions are favorable.

Optimum management of forest buffers around urban or industrial areas will be complicated by the effects of diurnal and seasonal variation in absorption. Ideally the pollutant emission could be timed to periods of optimum absorption by the forest; however, in most cases this is not practical. The more attractive alternative seems to be the development of a forest type that has good absorption characteristics during most of the year. Year-round uptake may not be possible in all climates. In the southeastern United States it is possible to grow large areas of coniferous species that have good sulfur dioxide absorption characteristics throughout the year. In colder or drier climates, vegetation uptake may not be as suitable because the major type of vegetation is deciduous, and the conifers have very slow metabolic rates at temperatures below freezing.

Therefore it seems that practical use of forests for air-pollutant sinks must rely on a combination of the proper species grown in the proper climate, with delivery of the pollutants at concentrations and times that favor uptake. However, even under less-than-optimum conditions, forests play an important role in pollution abatement. If the inclusion of a park or natural area in an otherwise urbanized space will decrease sulfur dioxide concentration during half the days in the year, this may be a very desirable use of this space when considered as part of a multipurpose park system.

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Acknowledgments. The authors acknowledge the contributions of Dr. R. L. Barnes, School of Forestry, Duke University, for discussion of the metabolic absorption by trees, and Dr. M. M. Pendergast, E. I. du Pont de Nemours & Co., Savannah River Laboratory, for information about atmospheric dispersion of air pollutants.

HUMAN PERCEPTION, SOCIAL FACTORS, AND ESTHETICS OF METROPOLITAN ENVIRONMENT

Ecology of an Urban Park

by DEREK J. COLEMAN, *president, Ecologistics Limited, Kitchener, Ontario, Canada.*

ABSTRACT.—A controversial issue in the city of Kitchener, Ontario, involves the proposed extension of a boulevard through Lakeside Park. A study of this proposal revealed several facets of human interrelations with an urban park. Most important, there was a large gap between the perception and the reality of environmental quality. This has several practical implications in planning parks in the city.

LAKESIDE PARK in the city of Kitchener, Ontario, (population 125,000) has been the center of controversy for almost a decade. To complete the network of major arterial roads in a section of the city, it will be necessary to construct a four-lane road through the park. Local residents, citizens groups, politicians, and municipal employees have been embroiled in lengthy debate on the issues. This is a report on some of the findings of a consultant's study of the issues.

In this case man is the significant determinant of the environmental parameters. This introduced a new element, because man's perception of the environment became the issue. There was a large gap between what was perceived to be the status of the environment and the actual case.

Lakeside Park is an area of 32 acres of varied vegetation and landscape. Of special prominence is a 4-acre lake in the middle of the park. Physically, it would be possible to avoid the lake in constructing the road. However, the potential destruction of this little gem of nature became a heated issue. The debate involved the lake, vegetation, wildlife, and recreation.

The study reported here included an examination of the status and interrelations of the physical and biological factors of the environment and an analysis of the park and its users.

THE LAKESIDE PARK ENVIRONMENT

Geology and Groundwater

This part of southern Ontario has been subject to several glacial advances from different directions. The most recent glaciation occurred during the Wisconsin period, 10,000 years ago. Kitchener is on the edge of a large interlobate moraine (the Waterloo Sand Hills), and typical conditions for this landform exist in Lakeside Park. Underlying deposits are varied in texture, and the general topography is rough. The lake itself is a kettle formation, resulting from the depression formed by a large mass of ice.

The park area experienced two periods of glaciation separated by a period dur-

ing which lacustrine clays were deposited. The material deposited during the first glacial period contains large quantities of sands and gravels accumulated to a thickness of 50 to 150 feet over the underlying bedrock. These deposits are water-bearing and are tapped by three municipal wells within the park. Lacustrine clays overlie this aquifer. The clay is, in turn, overlain by organic deposits in the immediate area of the lake and by glacial outwash materials beyond the lake.

The deposits immediately beneath the lake possess a very low permeability, providing a basin in which waters collect to form the lake. These deposits also act as a aquiclude (confining the aquifer below). Observation wells established that the lake is not a perched water table, as had been feared, but that the groundwater system is continuous with depth.

Water Supply and Quality

The lake as it presently exists has a surface area of 3.7 acres and ranges in depth down to 22 feet. As natural processes occur, the lake will gradually fill in with organic materials and waterborne solids. The total land area draining into the lake is 150 acres. The drainage basin is urbanized (except for the park), and three storm sewers discharge into the lake.

The total annual average rainfall in this area is 32 inches. This will result in approximately 150 acre-feet of water discharging to the lake. Drainage from the lake also drains into a small creek when the water level is above a certain elevation. For the rest of the year, there is no outflow. The water level in the lake drops below its outlet during dry periods because of evapotranspiration.

The lake in the park is one of the most eutrophic bodies of water in the Province. Eutrophication is a process whereby the nutrient level or fertility of a water body increases naturally as it ages. These nutrients stimulate the growth of aquatic plants, particularly algae, and the familiar problems of odor, weeds, and a deterioration in esthetics result. Eutrophication may arise through normal runoff and decomposition processes. The addition of storm sewage and runoff from fertilized lands accelerates the process.

Some of the water-quality data collected during study of the lake by the Ontario Ministry of Environment revealed coliform bacteria counts, nitrate nitrogen levels, and organic and ammonia nitrogen levels above the allowable limits for recreational use.

Nuisance water-pollution problems were identified as well. In several samples, the amount of oxidizable organic matter as measured by the BOD_5, COD, and volatile solids tests was greater than that normally found in surface waters. This suggested a high level of decomposition in the lake and the possibility of deoxygenation during nighttime hours. In the hypolimnion, with temperatures several degrees lower than the surface, the dissolved oxygen concentration approached 0 mg./1. Chloride ion, a common indicator of contamination by man, was measured in relatively high concentrations.

The major source of contamination in the lake seems to be storm-sewer discharges during periods of runoff.

Soils and Surficial Sediments

An examination of the soils and surficial sediments of the park revealed that the developed soil profile had been disturbed throughout most of the park.

Two large areas of fill material were discovered. Investigation of the filled area on the east side of the park revealed that this area had once been mined as a gravel pit and subsequently was filled with wastes and debris. The other area of fill was more recent. The upper park consists of stratified sands and fine gravelly sands, which have been remolded at some time.

Erosion of the steep embankments,

particularly on the eastern side of the lake, has been severe at various periods in the past. This is substantiated by the occurrence of soils consisting of 12 to 30 inches of sand loam and fine sands overlying 5 to 6 feet of organic and marl deposits.

Vegetation

Examination of the vegetation of the site, on air photos and in historic records, revealed that major changes had occurred in the past 25 years. Most notably, Dutch elm disease, land clearance, and filling have resulted in many large trees disappearing. The park does, however, support a diversity of vegetation communities from pond to marsh to upland. In a botanical survey of the site, 213 species of plants were identified.

All the vegetation in the park has been subjected to the influences of man. Characteristically, the vegetation is in secondary succession following severe disturbance. As a result, the canopies of most of the stands are open, with dense growth beneath. Many shrubs are present.

The east side of the park supports more natural stands of vegetation. The west and north sides are predominantly maintained lawns, except in the immediate area of the lake.

Wildlife

Inventories of birds and mammals of the park revealed a pattern of individuals and populations that related strongly to the vegetation structure. Thirty-nine species of birds were identified in the park. The diversity of species on the east side of the pond was identical (24 species) to that on the west side. Though the number of species on each side was the same, there were six species seen on each side that were not observed on the other. The east side had areas of denser tree canopy and more edge between woods and fields, thus attracting rose-breasted grosbeaks, eastern wood peewees, field sparrows and indigo buntings. The west side possessed more open fields, thus attracting species like kiildeer.

The diversity of bird species was related to the structural and botanical diversity of the vegetation. In the west, the cultivated landscape attracted only seven species, though it comprised 84 percent of the area. The more vegetationally diverse sections had 22 species on 16 percent of the area. The four vegetation areas with the most bird species contained a mean of 55 plant species each, which was almost twice as great as the mean for the four areas with the lowest number of bird species. The valuable habitats for birds were identified as those with both the largest amounts of high and low canopy and with the greatest vegetation diversity.

The most common species of mammals trapped in the park surveys were the white-footed mouse, the short-tailed shrew, and the meadow vole. Six of the seven vegetation areas in which small mammals were found are on the east side of the pond. All species prefer the dense herbaceous growth of the more natural environments. This is shown by a comparison of the mean percentage of shrubby cover in the vegetation areas where small mammals were captured (70 percent) with those areas where small mammals were not captured (31 percent).

Recreation

A survey of park users and activities showed several interesting patterns. The park attracts people from only a limited surrounding area, approximately ½ mile for most users. It serves the function of a neighborhood park, providing space for recreation to meet local demands. The people who do use the park do so frequently, averaging 4.8 visits per week. These people are predominantly children aged 1 to 12 and people over 65.

Observations on the spatial patterns

of the summer users produced interesting patterns. The highest concentration of users (32.7 percent) was in the playground off in one corner of the park. Walking, jogging, and the water-related activities showed medium levels of participation. Passive activities, such as sitting and sunning, bird-watching, and picnicking showed low levels of participation. The avoidance of the natural areas and attraction to facilities was obvious.

THE PARK ECOSYSTEM

When these various factors and conclusions were examined as a whole, several important conclusions became evident.

1. People focused on the lake as the significant natural feature of the park. It was perceived to be (by some knowledgeable people) very sensitive to the environmental effects of the proposed road. In fact, however, the lake was in an advanced state of eutrophication, in which many water-quality parameters were above recommended levels for contact recreation. The primary source of water to the lake was storm-water runoff. This rich environment had many benefits because it supported luxuriant aquatic vegetation and high populations of coarse fish for children to catch.
   This suggests that we do not necessarily require the achievement of a high-quality body of water for it to serve a significant amenity or recreation function. The eutrophic natural condition is stable and inexpensive when compared to the cost input necessary to artificially maintain marginally better conditions.
2. The terrestrial environment (soils, vegetation) of the park had been completely altered by man's actions in the past. The vegetation was predominantly early successional weed, shrub, and tree communities — not what one would consider particularly significant. However, because of its structural and vegetational characteristics and the diversity of habitat, the vegetation attracts an unusual number of bird species.
   Thus, although not important in itself, the vegetation of an area—even of 10 or 15 acres—can relate to substantial bird populations and provide a significant environmental resource within a confined space.
   One issue for environmental philosophers that is raised by this case develops from the preservation of the conditions in the park. If allowed to progress long enough, a more uniform and less attractive environment for birds will result. Thus, are we then justified in altering the natural processes to maintain a desirable situation that would extinguish itself?
3. Even though the natural features of the park were perceived as being its outstanding characteristic, particularly by the vocal environmental groups, the average park user did not attempt to come in contact with the more natural areas — except for the young who played on the pond edge. The patterns of man and nature did not overlap. The local naturalists were such a low percentage of park users that they were not recorded during the surveys.
   Thus, in planning for nature in our parks one must ask for whom certain elements are preserved.
   Since the spatial patterns of the recreationists and nature did not conflict in this case, it suggests that careful planning can resolve problems of incompatibility.

Man-made New Orleans: Some Interactions between the Physical and Esthetic Environments

by RONALD F. LOCKMANN, *assistant professor, Department of Anthropology and Geography, University of New Orleans, Lakefront, New Orleans, La. 70122.*

ABSTRACT.—The relations between the physical environment and esthetic dimensions of the New Orleans cultural landscape are examined. The esthetic characteristics associated with New Orleans urban morphology are examined with respect to possible constraints by the physical environment. Salient townscape features such as street grid system, surface-drainage network, and spatial features of selected residential neighborhoods provide instances that demonstrate the varying levels of physical environmental impingement upon the esthetic landscape.

Because of its close, if not abject, dependence upon local building materials and local qualities of site, the city epitomizes the surrounding country and gives a special character to the natural setting. At no moment in its existence is the divorce between the man-made environment and the earth complete.

—LEWIS MUMFORD, *in The Culture of Cities*

THE NEW ORLEANS urban complex stands upon what has been termed the flattest, lowest, and geologically youngest site of any major city in the United States (fig. 1). The site has been above sea level for roughly a thousand years, while the most significant human landscape modification has transpired roughly within the past two centuries.

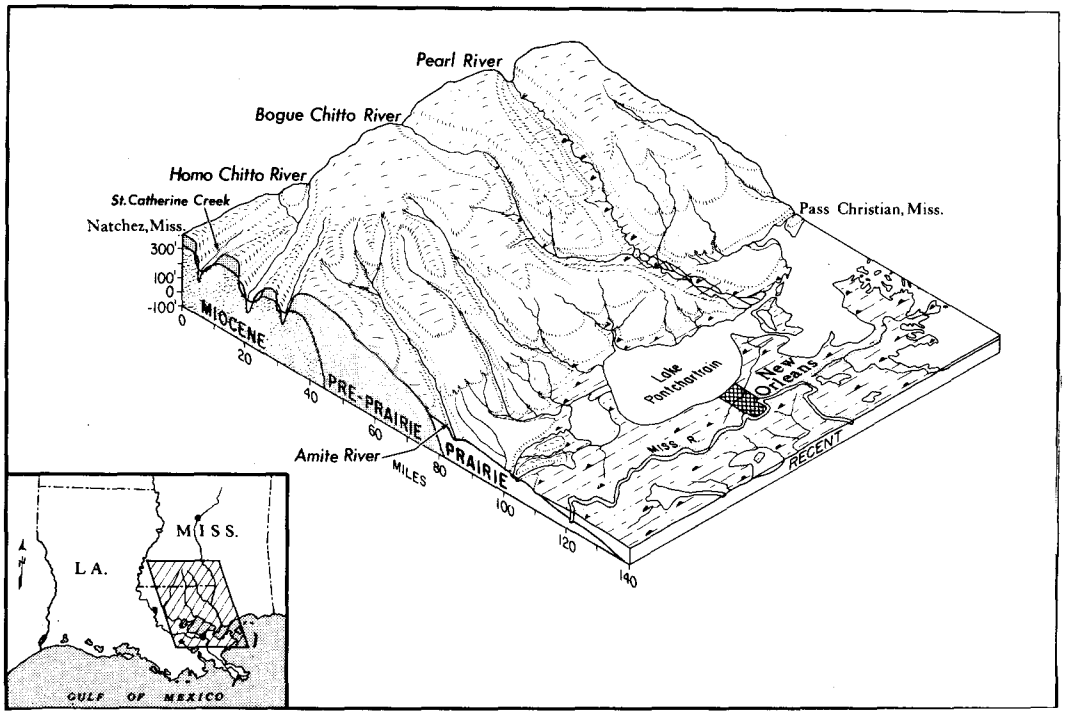
The growing demands for space to accommodate the population of one of the world's major ports have transmogrified the physical landscape of New Orleans so fundamentally that the designation — man-made — applies not only to buildings, roads, and other components of the cultural landscape, but also to the undulations of the land surface itself. Indeed, the processes of site preparation and maintenance (that is, from extreme meteorologic or hydrologic events) have built a virtual walled city that is primarily below sea level, and portions of which, in geological terms at least, are subsiding rapidly.

The visual or esthetic landscape is compounded of the disparate elements of the physical and human scene, and it becomes chaotic and illegible in certain locales as a result of the uneasy symbiosis of man and nature. Especially the street grid, drainage system, and spatial structure of certain residential neighborhoods give visual evidence of the inextricably interwoven physical and human landscapes.

ASPECTS OF THE PHYSICAL MILIEU

New Orleans' global importance as a port followed from its geographical location on the lower deltaic plain of North America's premier river. The "Isle of Orleans" depicted by the eighteenth century cartographer Delisle is reality when one considers that marshlands flank the city's eastern and western edges, and the banks of Lake Pontchartrain on the north and the Mississippi to the south are permanent, though dynamic, physical boundaries. The characteristics of the land surface have long confounded potential residents as well as visitors, as an eighteenth century account affirmed:

Figure 1.—Block diagram illustrating geologic structure and geomorphology of New Orleans region in southeastern Louisiana. Courtesy Dr. Sherwood M. Gagliano.



At high tide, the river flows through the streets. The subsoil is swampy... Dikes have to be built along the river, and houses can be constructed only on piles. Those living in the city... feel as if they were living on an island in the middle of a mud puddle. *(Regional Planning Commission 1969)*

The alluvial ridges or levees built by the Mississippi River's overbank flow at high stages provided the highest ground, although they stood no more than 10 or 15 feet above sea level. In addition to the natural levees, less extensive former beach ridges were deposited above the generally sea-level fresh (some brackish) water marshes, while thickets of cypress dominated the swamps. Much of this area, most of the present urban region, is thus below sea level, thereby accounting for the popular concept of a bowl-shaped base on which New Orleans is situated.

The former beach ridges, called Metairie and Gentilly ridges, (also called Metairie Bayou and Bayou Sauvage (figs. 2 and 3) provided the road surfaces, west and east respectively, giving first overland contact to the town of New Orleans.

IMPACT OF HUMAN MODIFICATION OF THE LANDSCAPE

The locale of New Orleans proved attractive for the aboriginal Amerinds who occupied the region for more than 2,000 years. The Europeans realized, as early as 1699, the strategic value of the Bayou St. John portage route between the Mississippi and Lake Pontchartrain. The natural levees were a stable and partially dry foundation for the original settlement's nucleus. Thus the French Quarter is situated on some of the highest ground in the region.

Yet from the very beginnings, the concern for flood control, or protection, by walled dikes was paramount. In 1722, the engineer La Tour urged the

Figure 2.—Regional geomorphology of New Orleans in the Pontchartrain Basin vicinity. From Saucier 1963.

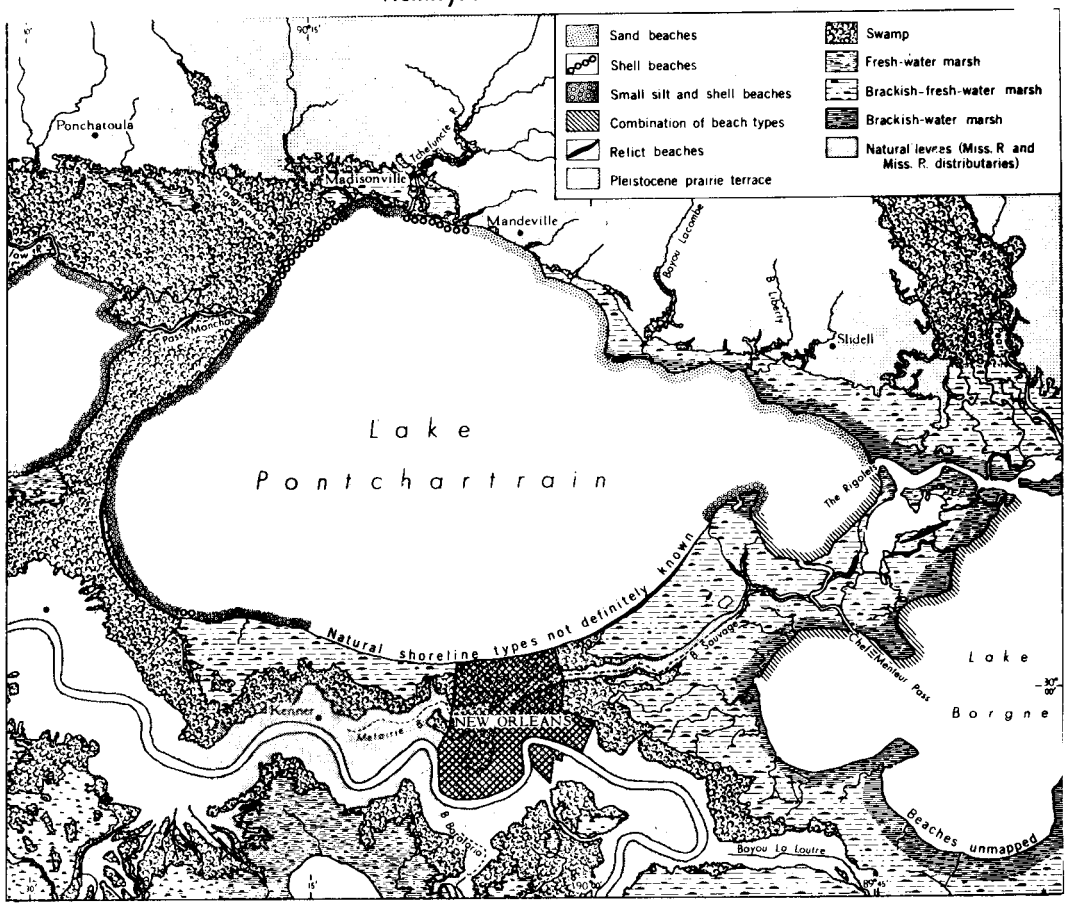
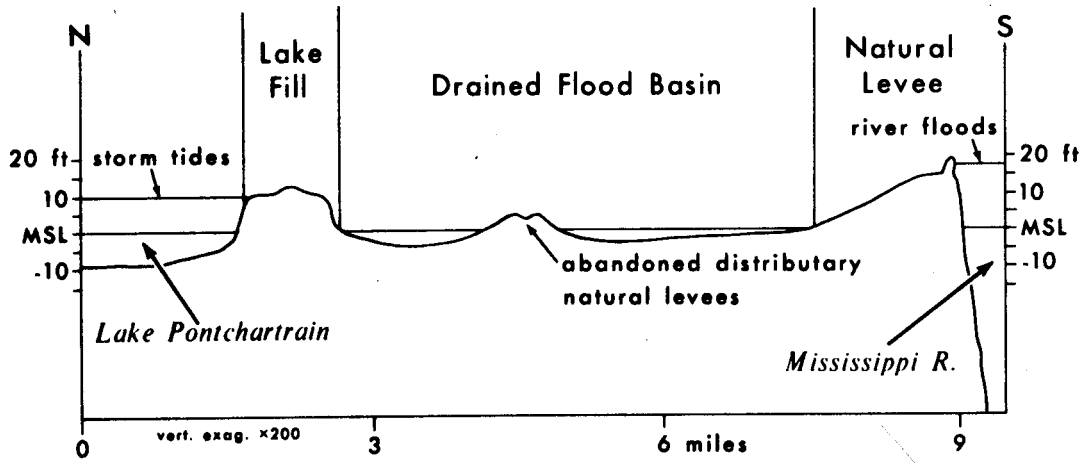


Figure 3.—Typical north-south profile through city of New Orleans. Courtesy Dr. Sherwood M. Gagliano.

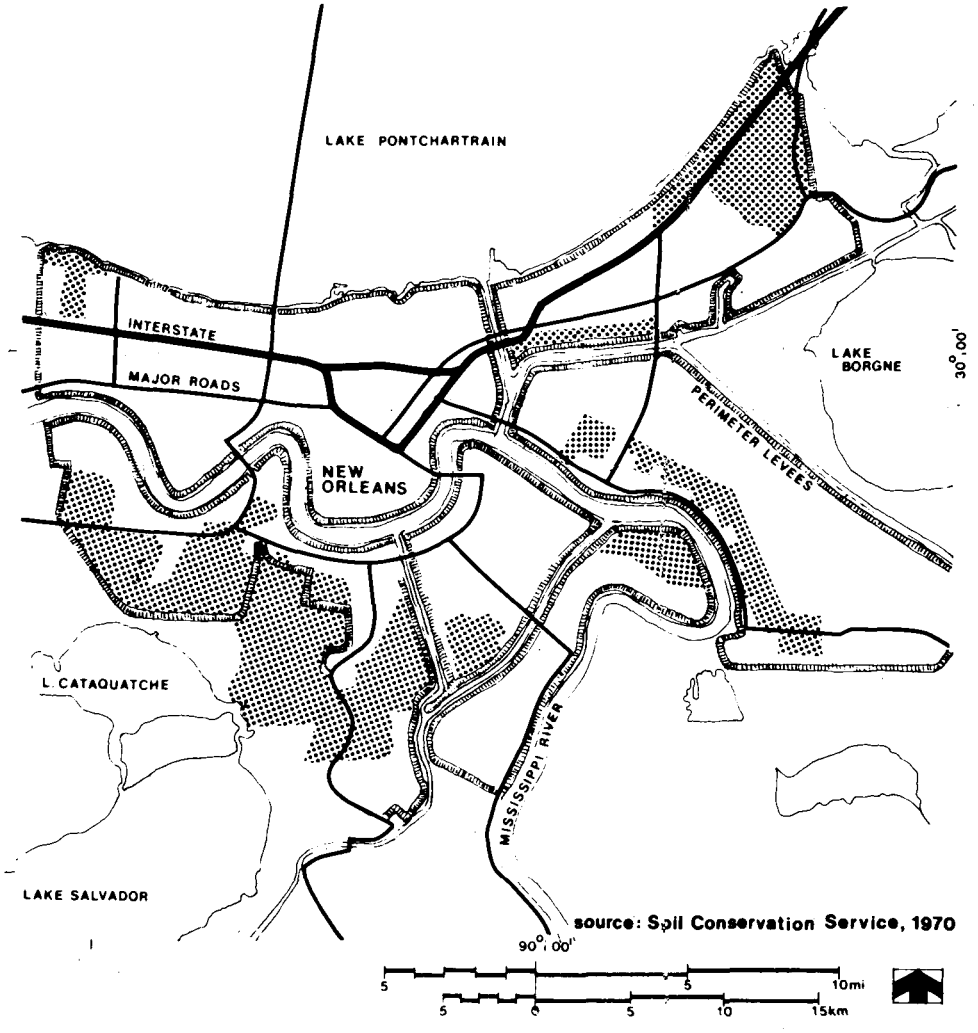


construction of higher and wider dikes than those already being built. And nineteenth century maps clearly depict the correspondence of urban morphology and the higher ground of the natural levees. A Mississippi River Commission report in 1896 indicated that at least half of the land inside the present-day city limits remained swamp and marshland. The nineteenth century saw cycles of levee building and subsequent destruction by major floods.

At present, the Army Corps of Engineers builds the levees in the New Orleans area, and local or parish agencies retain the responsibility for their maintenance. The system consists of levees on both banks of the Mississippi, averaging 25 feet (7.6 m) above sea level. Thus New Orleans' site is likened to a high-rimmed saucer. The levees may keep the river from entering the city, but they have also served to retain whatever water may enter.

The city averages more than 60 inches (150 cm.) of precipitation yearly; and disposal of excess water was one of the historic urban woes in New Orleans (*Jennings 1972*). It was only in 1917, upon the employment of the electric

Figure 4.—Areas surveyed by Soil Conservation Service, 1970, showing soils potentially unsuitable for urban construction. Courtesy Dr. Dan W. Earle.



screw-type pump, that the swamps and marshes were drained and the city's fringe could advance in subsequent decades through the mid-city district and towards the lakeshore. As recently as the late 1920s, the Lake Pontchartrain shore was, with few exceptions, a swampy isolated expanse with permanent settlements consisting mainly of ramshackle fishing camps (*Filipich and Taylor 1971*). The east and west roads out of New Orleans, on Gentilly and Metairie ridges respectively, contained the preponderance of suburban population. As recently as 1940 New Orleans had, among major American cities, one of the lowest ratios of population residing outside the city limits (*Gilmore 1944*). Since the urban region's population has nearly doubled in the span from 1940 to the present, the main era of extensive wetlands drainage to facilitate residential construction has occurred recently (fig. 4).

LOCAL VISUAL QUALITIES AND THE NEW ORLEANS ESTHETIC LANDSCAPE

Tourism is commonly cited as the second leading industry of the New Orleans economy. Certainly the widely held city image of an uncommonly scenic and distinctively old-world townscape is a part of the lure that attracts large numbers to visit New Orleans annually. The obvious attractions are the French Quarter and the ante-bellum residential Garden District. It may not be readily apparent that these neighborhoods stand on some of the higher ground in the city. Nor is one palpably below sea level in certain adjacent areas.

Reading the local landscape is further complicated by the commonplace realization that the French Quarter's cracked and disjointed sidewalks, an occasional tilted house, or sagging fences in the Garden District are conditions to be expected in historic areas and are hardly unique to New Orleans. Relatively few tourists expend the effort to view any of the dozens of other local neighborhoods or suburban outliers of New Orleans. It is therefore possible, and even easy, to miss the subtle but nonetheless prevalent visual clues and tangible landmarks that epitomize the problems of construction on an unstable foundation.

The New Orleans esthetic landscape is a product of the structures and spaces man has superimposed on a physical base, and yet the very base itself has become a man-made object that gives an overtly distinctive appearance to large sections of the urban region. The intricate interrelation between man's modification of the physical environment and its reciprocal impact on structures and general surface characteristics can be illustrated by a consideration of street patterns, drainage systems, and land subsidence in selected portions of New Orleans.

STREET GRID

The distinctive overall feature of the road pattern of New Orleans as seen from the air or map view is the fan-like layout of streets on that lobe of land enclosed by the crescent bend of the Mississippi River. Adjusted to the configuration of early land-ownership boundaries, the configuration is not a direct response to physical conditions. The more common rectangular or checkerboard street pattern, with roads intersecting at right angles, is characteristic of most of the rest of the New Orleans region and suburbs, except where developers have built winding roads and cul-de-sacs in recent subdivisions.

Spatial or directional orientation is a persistent malaise affecting lifelong New Orleanians as well as tourists. Though this affliction may be understandable in the vicinity of extended curvilinear roads and triangular blocks in the fan-shaped Uptown and Garden District, it is apparently just as common for the presumably more logically

arranged rectangular districts. These latter patterns now largely occupy the former open spaces between the network of drainage canals that turned them into dry land.

A popular solution to the complexities of local geography is location fixing with reference to the Mississippi River and Lake Pontchartrain. The location of a residence, for example, is either "riverside" or "lakeside" of, for example, the main interstate highway that bisects much of the urban area (fig. 4). Another local practice to simplify direction giving is the use of the terms "above" and "below" for distinguishing points on either side of a given boundary (particularly streets), generally with reference to the central business district. In the context of a city with considerable sub-sealevel land, this particular local trait is potentially confusing, indicating to outsiders that New Orleanians possess some remarkable perceptual acumen and are intimately aware of the nuances of local topographic undulations. This is most assuredly not true, and "above" and "below" are strictly horizontal references and not elevation indicators.

Passengers in a vehicle or pedestrians who turn off the major commercial and connecting thoroughfares notice the predominantly narrow streets in most of the older neighborhoods. Although narrow streets are hardly a unique New Orleans trait, their prevalence underscores, along with the typically long and narrow lots, that space has been at a premium in this city.

The condition of the road surfaces reflect the stresses of overlaying a differentially sagging foundation. Off the main traffic arteries, warped, cracked, caved, and potholed road surfaces are common. Yet roads often mark the neighborhood's highest local relief. And in areas lacking some variety of curbing, clam shell and deeply indented mud shoulders further contribute to an overall impression of disarray and instability.

WATER-REMOVAL STYSTEM: CANALS AND DRAINAGE

Street orientation in New Orleans exhibits a strong general correspondence with the drainage network. And since the network provides daily removal in the basin as well as affording drainage for heavy storms and flood occurrences, it is a crucial to the continuance of urban utilization of the site. By 1970 the Parish of Orleans alone boasted 1,400 miles of drainage canals and the 13 pumping stations, probably the greatest aggregation of low-lift pumps assembled anywhere in an equal area (*Carter 1969*), with an aggregate capacity of 17.5 billion gallons (65 million liters) per day.

Canals range in size, some being as much as 80 feet (24.5 m) wide. Features of this magnitude are indeed prominent landmarks and boundaries in the visual landscape. The open canals also assault the olfactory senses when flow is slight, giving false credence to the occasionally published misstatement that New Orleans employs open sewers.

Canals are perhaps less obvious in the older sections of the city, where many were covered, than in the more recent subdivisions, where housing construction followed close upon canalization and covered canals are an unaffordable luxury.

It is terribly easy to underestimate the extent of the New Orleans region's drainage system based on direct observation, but the impact of the system is more profound than keeping excess water from the streets and forming barriers to the flow of traffic. The continued action of the drainage process is fundamental to the gradual lowering of the land surface itself (*Gagliano 1973*). This process, which requires expensive maintenance of the flood-protection landform complex, and

the gradual moving and tilting of structures built on the surface of a differentially undulating topography, is among the chief features of the New Orleans esthetic landscape.

LAND SUBSIDENCE: THE CHANGING NEW ORLEANS SCENE

The phenomenon of land subsidence is among the paramount physical processes impacting on urban expansion in the New Orleans metropolitan region. It has been succinctly defined by Saucier (*1963*) as the relative lowering of the land surface with respect to sea level. More recently Earle (*1975*) has pointed out that the term is often invoked with reference to tectonic occurrences over a larger region whereas "settlement" usually refers to a less extensive area and the changing compaction of soil. The term "lowering" is employed in regards to road, building, levee, or other compression of underlying soil. The popular equivalent of "subsidence" is "sinking".

Land subsidence is a global nuisance and many cases have been closely observed and documented. This phenomenon has occurred in London, England; Osaka, Japan; Lake Maracaibo, Venezuela; and Mexico City to name a few notable examples. In Mexico City an exposed well casing in the Plaza de la Republica, originally flush with the surface, was measured at 23 feet (9 m) above the present after about 60 years of use (*Fox 1965, Legget 1973*).

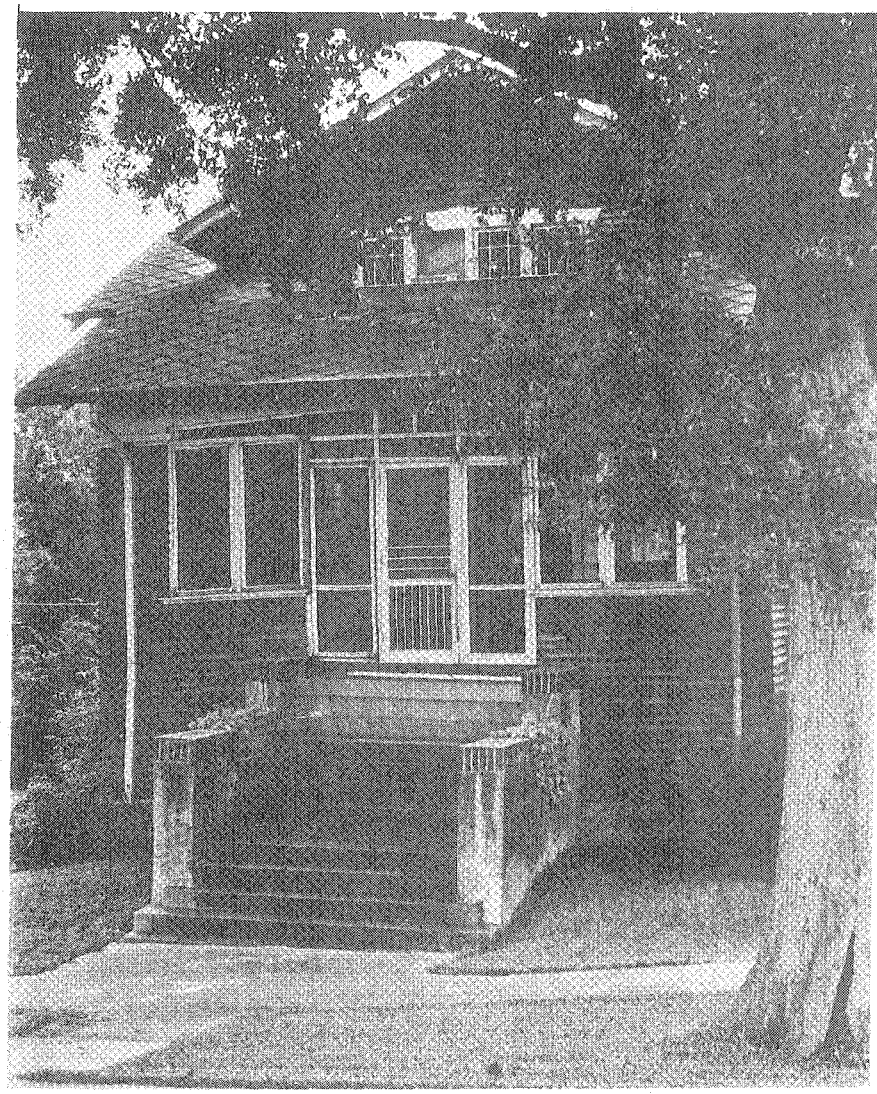
In the United States, land subsidence is by no means uncommon. Owing, perhaps, to the somewhat less extreme nature of land subsidence, New Orleans is not mentioned in most of the standard subsidence literature, although the extent of the local problem is visibly apparent throughout the metropolitan area and especially in a few noteworthy neighborhoods. In the drained wetland regions such as New Orleans, the complexity of organic soils makes it difficult to relate subsidence to a single cause. The major factors impinging on land subsidence rates in New Orleans are: dehydration and shrinking of the deposits; oxidation of organic substances; the drop in the local water table; and excavation for sewers and water lines. Some local soil types may contain 4 to 12 feet of compressible organics, and the water content of humus may be 400 to 700 percent of dry weight (*Soil Conservation Service 1970, fig. 5*). A series of level surveys in the organic soils of the Florida Everglades measured an 8-foot (2.5-m) drop in surface over a span of 50 years of regular measurement (*Stephens and Speir 1970*).

Land subsidence in the New Orleans metropolitan area is prevalent in virtually all neighborhoods, but a few districts in particular epitomize the problematic extremes of this phenomenon. Cracks, broken, and undulating sidewalks; tilted houses and other structures; inclined tree trunks and utility poles; and undulating lawns, and other open-space surfaces are virtually ubiquitous manifestations of the semi-fluid regional substrate.

The older neighborhoods may be relatively less affected, yet in the established districts of Carrollton, Mid City, or Lakeview, each with sub-sealevel areas, scarcely one block exists without numerous visual symptoms of subsidence (fig. 5). In the highest and oldest portions of New Orleans, numerous structures have lasted for many decades with negligible tilt or settlement.

For this reason, foundation support by pilings or caissons are not mandatory for construction in the metropolitan region. On the other hand, the largest structures such as the 60-storied One Shell Square Building or Louisiana Superdome have had steel or concrete pilings extended beneath their foundations to between 100 and 150 feet (31 to 45 m). Most residential construction, employs log pilings about 40 to 50 feet (12 to 15 m) in length, which is generally sufficient to ensure structural

Figure 5.—Residence in 6300 block, West End Boulevard in Lakeview section, New Orleans. Note undulating sidewalk as well as cracked and tilted stairway.



stability in most locations in the region. But since the necessary drainage system tends to lower the previously higher water table, followed by oxidation and compaction, most of the urban complex experiences the effects of subsidence (*Gagliano 1973*). On the formerly sea-level drained marshland on the eastern and western suburban fringes of New Orleans, two subdivisions stand in mute testimony to the extreme and dramatic impact of land subsidence in the region.

LAND SUBSIDENCE: EPITOME DISTRICTS

Village Del'Est is a subdivision in the eastern part of the city of New Orleans, built in an area long avoided for urbanization because of its marshy foundation. The Harold Park section is located in the municipality of Kenner, immediately north of New Orleans International Airport and was built as the population of New Orleans' western suburban fringe expanded during the

past 20 years. In the span of time since they have been completed—and there are still vacant lots in both areas—these districts have provided some of the most striking examples of physically and visually blighted portions of the New Orleans area. Tilted structures exposed foundation slabs, cracked walls, driveways and sidewalks, and leaning fences and utility poles are among the most vivid visual impressions of both of the subdivisions; and few blocks in either one has two adjoining houses without one of these problems.

Few industrious residents have been able to maintain the original appearance of their premises, and many have long since stopped trying. Buying loads of fill soil to bring up levels to original is a prevalent practice in suburban as well as older New Orleans districts, but one truck-load would hardly suffice in Village Del'Est or Harold Park. One section in Kenner experienced sinking of as much as 1 foot in a month's time (*Aquanotes 1975*). The expense of filling large tracts has led developers to disregard realistic estimates of potential subsidence on the drained wetlands underlying these and other subdivisions. In one segment of the Village Del-Est, one 760-acre (308-ha.) plot was filled with 630,000 cubic yards (481,666 m^3) of material to raise the surface 6 inches (15.2 cm) above the original level. To add another vertical foot would have cost the developer $3,030 per acre (*Earle 1975*). It is thus understandable why the developer estimated that potential subsidence would be 6 inches to 1 foot!

In Harold Park, Kenner, as well as in other locations, some developers reduced their cash outlays by eliminating the foundation pilings. The result is several blocks of moderately to severely tilted houses. The corner of Arkansas and 32nd streets provides one striking

Figure 6.—Residence at corner of Arkansas and 32nd Streets, Harold Park subdivision in Kenner.

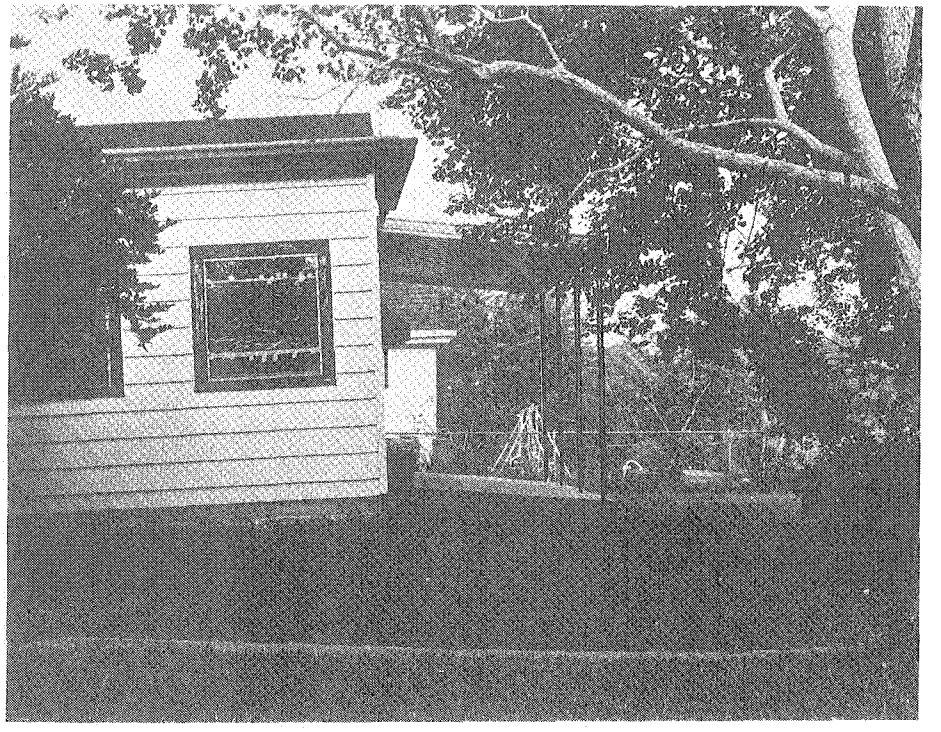


Figure 7.—Residence at 4211 Williams Boulevard, Kenner. Support pilings appear to be stilts. Note incline of unsupported concrete pad.

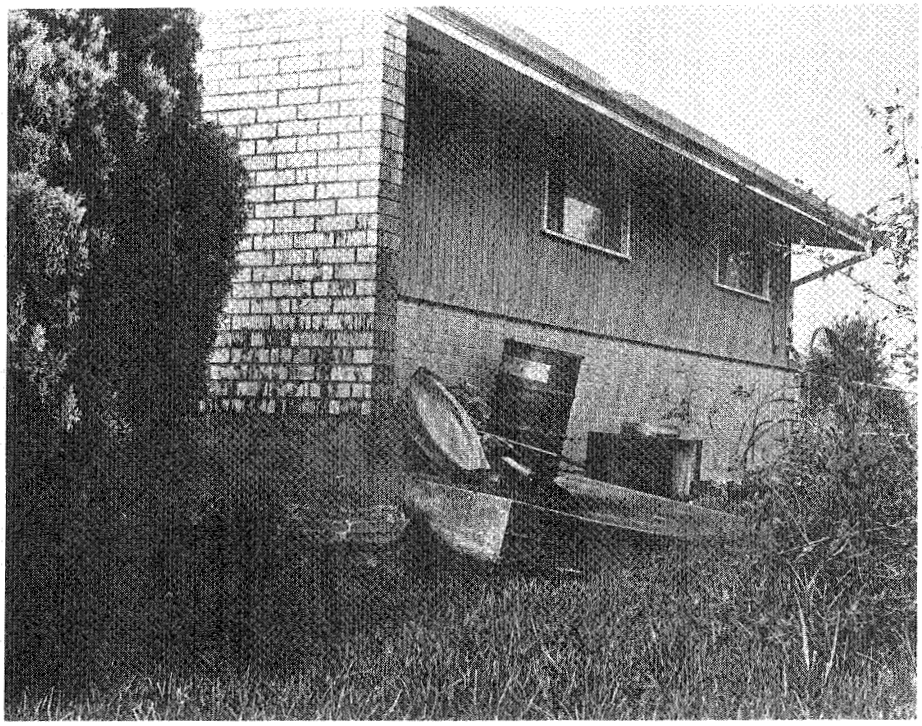


Figure 8.—Residence in 3200 block of Colorado Street, Harold Park subdivision, Kenner.

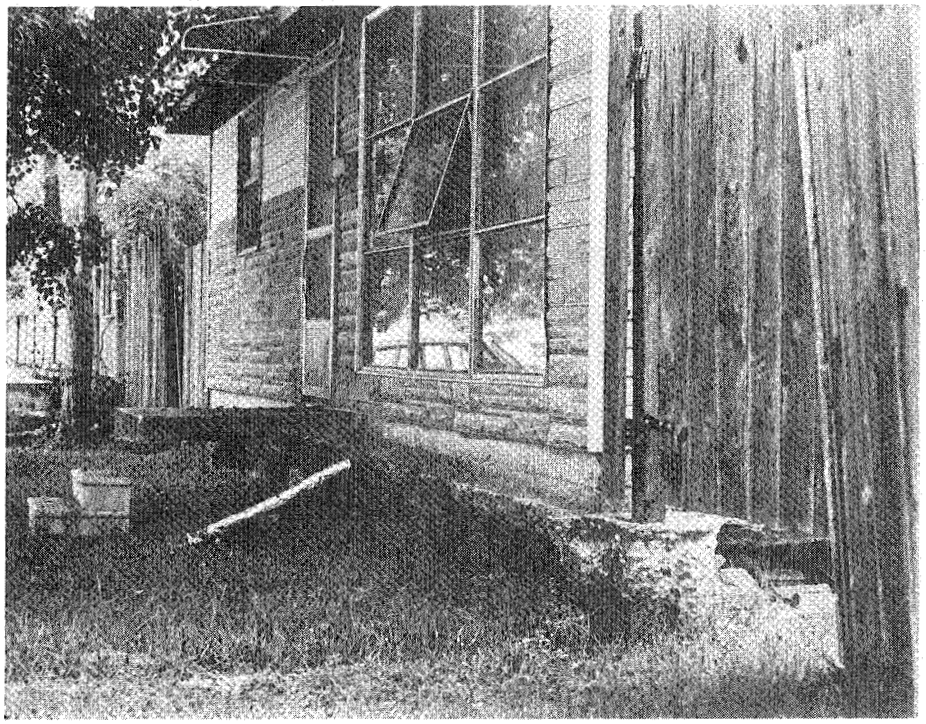
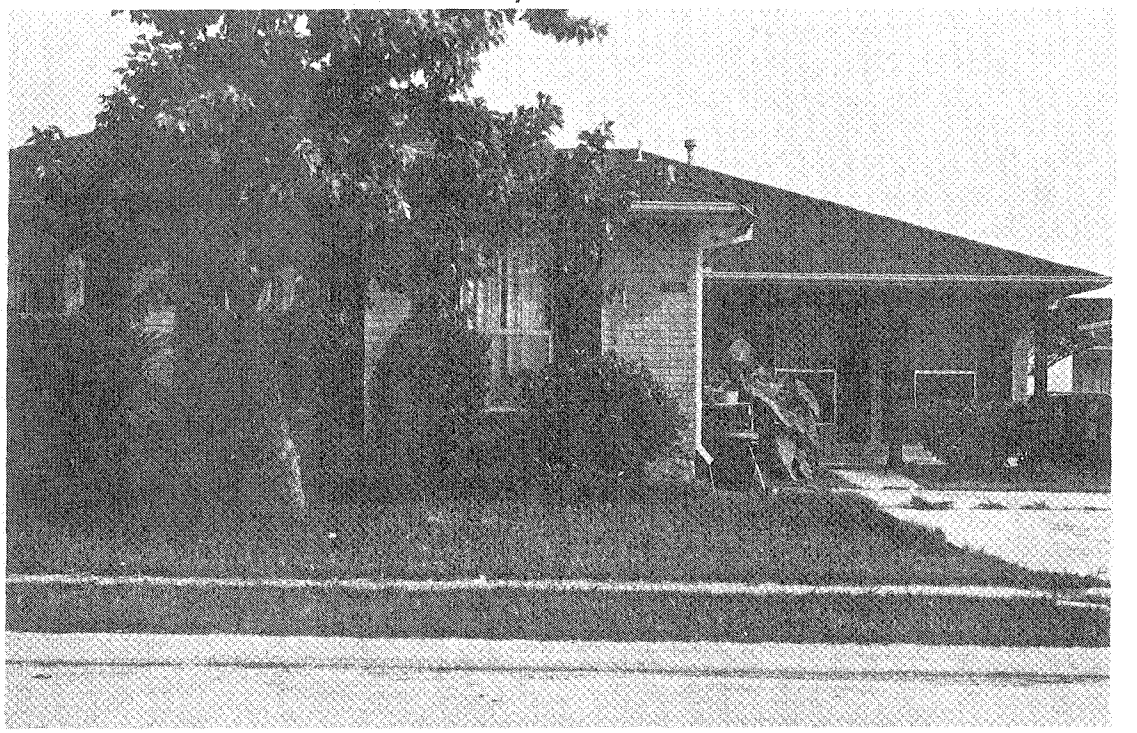


Figure 9.—Residence in 13000 block of N. Nemours, Village Del'Est subdivision, New Orleans. Ornamental plantings obscure exposed foundation bottom directly behind tree.



visual example of structural movement and damage (fig. 6). Even many of the buildings supported by pilings have been affected to the extent that undersides of foundations and even the pilings are above present ground level, giving the appearance of low-level stilt houses (figs. 7 and 8). Some Village Del'Est homes have undergone the same forces, the subfoundation space providing den or nesting sites for domestic animals and wildlife from adjacent marshlands (*Carrier 1975*).

Adroit placement of foilage is sometimes successful in masking the extent of subsidence (fig. 9), although some residents have decided to remove larger shrubbery and trees when soil-creep moved root systems and trunks toward the foundation hole. Piles of earth fill are among the most pervasive of visual landscape characteristics in Village Del'Est. Along many streets, such as N. Lemans, scattered piles of earth fill have formed a hodge-podge of domal and conical hillocks, many at least partially overgrown with tufts of weeds and grass, while some have become overgrown and entirely incorporated into the lawns. The billowy undulations and the welter of unkempt yards, devastated foundations, fences and sidewalks (figs. 10 and 11) combine to invest the esthetic landscape with a chaotic and blighted guise starkly contrasting in extremes with the subdivision's original and intended appearance.

In Village Del'Est, as elsewhere, esthetic environment manifests itself in financial considerations. In Village Del'Est, the average expense per year was calculated to be $120 for about two-thirds of the residents; nearly one-third had expenses in excess of that figure, and some 5 percent of homeowners in the tract reported annual costs of over

Figure 10.—Warped and cracked sidewalk on corner of E. Lemans and Dwyer Streets, Village Del-Est subdivision, New Orleans.

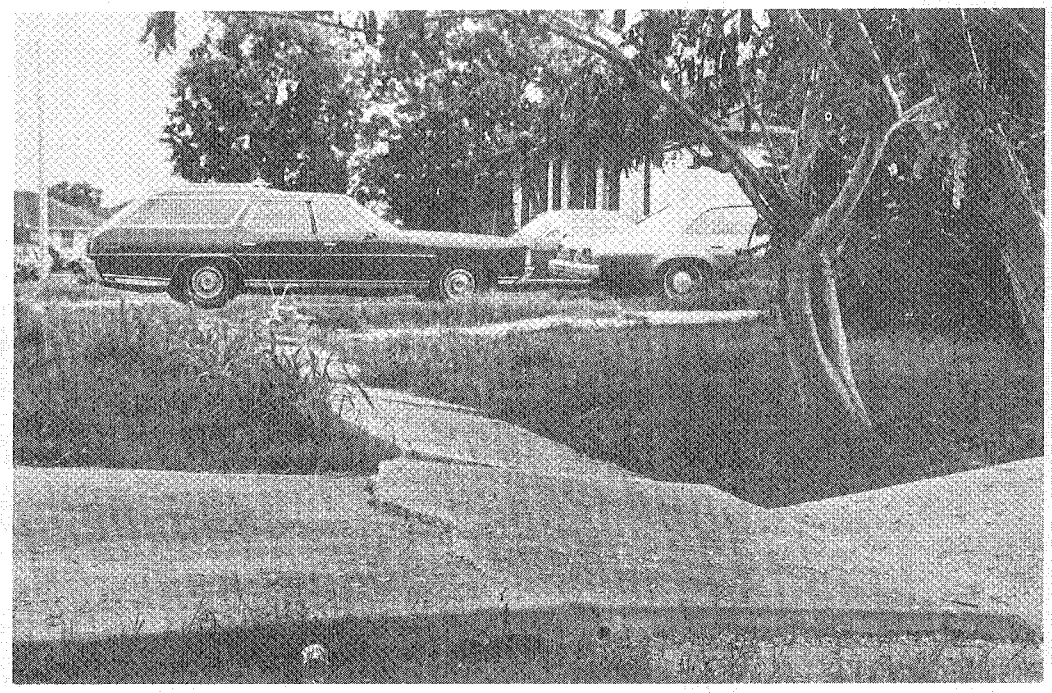


Figure 11.—Residence at 4309 Williams Boulevard, Kenner, with advanced tilting and cracking of low brick wall.



$600. One house experienced settlement of more than 11 inches (27.9 cm) in a 6-month span owing to a water-table change after adjacent construction. Shoring repairs on this property were estimated at $5,000, while other owners have paid between $1,200 and $6,000 for such work. Despite hopes of appreciation of about 2 percent per year, some have experienced a depreciation of as much as 25 percent in less than a decade (*Earle 1975, Carrier 1975, Aquanotes 1975*). In both the Village Del'Est and Harold Park subdivisions, the plethora of FOR SALE signs, added to the variety of other visual cues, is a further indication of consumer dissatisfaction with these problematic areas.

SUMMARY

The New Orleans esthetic landscape is the product of a melange of disparate influences, among which street-pattern orientation, drainage network, and especially topographic fluctuations resulting from land subsidence are most striking visually. While some districts provide more extreme and obvious cases of physical-esthetic interactions, these influences are nevertheless general throughout the entire urbanized region. Except for the most blatant and severe sorts of disruption, New Orleans residents seem to have implicitly accepted the gradual but perceptible change in form of their shared plot of ground as yet another part of the local ambience. The man-induced transformation of the New Orleans landscape has modified physical processes that are changing the surface configuration of the ground. This dynamic, almost fluid, nature of the land base is one of the paramount determinants of those visual qualities that constitute the New Orleans esthetic environment.

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Acknowledgments. The author thanks the following for aid and encouragement: J. Richard Shenkel and David O. Roberts, Department of Anthropology and Geography, University of New Orleans; Robert Cunningham, U. S. Army Corps of Engineers; Sherwood M. Gagliano, Coastal Environments, Inc., Baton Rouge, Louisiana; and Dan W. Earle, Jr., Department of Landscape Architecture, Louisiana State University, Baton Rouge.

Visual and Functional Components of the Built Environment: A Case Study of Urban Residential Neighborhoods

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ABSTRACT.—The hypothesis that visual and functional characteristics of neighborhoods influence the psychological well-being of residents was tested. An informal test by a survey of advertising strategies for selling real estate was first used. Second, data from a variety of published sources were used to identify some of the underlying dimensions of residential neighborhoods. The dimensions were used as independent variables to predict three different measures of psychological well-being in former mental patients. The results partially supported the hypothesized relationship by demonstrating that neighborhood type appeared to influence the patients' recuperation.

MY CONCERN IS the relationship between physical setting and human well-being in residential neighborhoods. It will be argued that an individual's neighborhood has a significant influence, both visually and functionally, on his or her psychological well-being. Background for these assumptions has been assembled in a variety of sources (*Angrist 1974, Peterson 1967, Smith 1975*), which have made important contributions to burgeoning disciplines such as behavorial geography and environmental psychology (*Proshansky et al. 1970, Downs and Stea 1973, Amadeo and Golledge 1975, Zube et al. 1975, Lang et al. 1974*). To substantiate these assumptions, I will describe a study designed: (1) to characterize some of the underlying visual and functional dimensions of residential neighborhoods, and (2) to test for a relationship between those dimensions and the psychological well-being of the residents.

I attempted to investigate characteristics of residential neighborhoods by analyzing the sales strategies adopted by realtors. It is reasonable to assume that sellers of residential units describe to potential customers the benefits they will realize if they choose to live in a particular neighborhood. We can also assume that the buyers expect to realize at least some of these benefits.

RESIDENTIAL NEIGHBORHOOD AND PSYCHOLOGICAL WELL-BEING

A city exists primarily to concentrate services for a large population in a relatively small area, and one of the most important of these services is providing people with a place to live. The residential unit and its adjacent neighborhood invariably become the spatial domain of the modern western person. Most of us spend at least two-thirds of our lives in and around the home, and some spend considerably more. Thus, although the neighborhood provides shelter, it may do much more; in fact the neighborhood can make us feel good or bad in varying degrees. A neighborhood may be pleasant to look at, it may be a happy place, and it may have a strong sense of community. On the other hand it may be ugly, anonymous, or sad.

It is convenient to class neighborhood characteristics into visual and functional components. Thus a neighborhood is first something we look at; and when we look, we may see features which please or displease us. We tend to look for trees, or hills and streams;

but often we see only factories, parking lots, and cars. At the same time, we interact with our neighborhood in other nonvisual ways. We live in a certain spatial unit, we move around in it, socialize in it, and breathe its air. Obviously the physical layout of the neighborhood, the amount of vehicular traffic, and its social composition, among other things, will influence the way we feel these interactions. In other words, the neighborhood may help or hinder our everyday functioning and the way we go about taking care of our needs.

Robert Sommer *(1974)* has recently developed this argument, at a more general level, in a book titled "Tight Spaces". Sommer described two distinct types of physical settings, one which is "hard" and unresponsive to human needs; and another which is "soft" and more likely to "welcome and reflect the presence of human beings."

VISUAL AND FUNCTIONAL COMPONENTS OF NEIGHBORHOOD: SOME IDEALIZED STATEMENTS

When a real-estate agent advertises a property, he tries to enhance the good points and minimize the not-so-good. Much of his selling strategy is concentrated on the residential unit, but often the neighborhood characteristics are included. In these cases, the information provided may be spatially bounded, to describe, for example, the view from the kitchen window. In other cases the information is aspatial in nature, for example, to describe the security or the type of neighbors one might expect to find. The information varies with the type of unit being sold, the income and age group of the prospective buyers, and the location of the property.

Nevertheless, by looking at the descriptions used in advertising residential property, we can get some indication of the ways the realtors expect the property to enhance the quality of an individual's life. Although the descriptions represent an idealized picture, as is the case in most advertising, we must assume they are based on some elements of truth, embellished in varying degrees by subjective evaluations.

Method

The Sunday newspapers of nine cities in the United States were analyzed for 4 consecutive weeks. They included a range of sizes and locations: New York, Los Angeles, Detroit, Dallas, Atlanta, Tulsa, Oklahoma City, Ann Arbor, and Norman. All advertisements in the real-estate pages were subjected to a content analysis, but only statements pertaining to the neighborhood were considered. No attempts were made to define "neighborhood" specifically, but it became apparent that any information that did not relate specifically to the residential unit or the apartment complex, should be considered.

In general, the search was for the adjectives and phrases used to describe the area in which the units were located. From the content analysis, a list of descriptive neighborhood features was generated, and a small sample of them is reproduced in table 1. It was evident that the descriptions were related to a variety of needs and desires that would appeal to the potential buyer, and some of these are suggested.

To organize the list of features and their related needs, the information was categorized heirarchically along the lines suggested by Abraham Maslow *(1968)*. Obviously it was not possible to defend rigorously the categorization shown in table 1, and there is no hard evidence to link the items with any of Maslow's needs. Similarly, each of the described features could be related to the satisfaction of more than one type of need. The table was constructed solely as a mnenomic device, and as a way to make some sense out of an extremely diverse set of needs and desires.

In selling a neighborhood, we can assume that the realtor believes, and would like the buyer to believe, that

Table 1.—Selling neighborhoods according to human needs*

	Examples of neighborhood descriptions in advertisements	Related needs and desires	Maslow's needs
1.	"Finest shopping close to Detroit" "Competitive rents" "Only 42 minutes from New York City via New Jersey Turnpike" "Save a fistful" "On a clear day you can see Big Boy"	Economy, accessibility, spaciousness, recreation convenience	Physiological
2.	"Fox Briar Estates is trees, trees, trees . . . is Edmond Schools . . ." "Great place to bring up the kids" "Safe streets, safe neighborhood" "To keep you from turning green a 24-hour security patrol and staffed gatehouse"	Security, safe for children, privacy	Safety
3.	"A unique community, friendly neighbors" "Creeks and wooded cliffs" "Rambling stone walls and open meadows . . . Canadian Geese and clear skies" "Rustic elegance . . . On a Sunday afternoon you see more horses than cars"	Sense of community neighborliness, friendship, trust, close to nature, esthetics	Love and belonging (natural and human)
4.	"Prestige living in the fashionable sixties" (New York City) "We only look expensive" "Quality . . . and then some" "Dream neighborhood . . . luxurious"	Luxury, quality status, elegance, excitement	Esteem
5.	"Live in a real townhome community, in town . . . in Dallas' prestigious eclectic neighborhood" "Avoid houses built in patterned conformity" "The best of everything" "Where you would like to spend the rest of your life"	Individuality, distinctiveness	Self actualization

*Needs are categorized according to Maslow's heirarchy (see text). No attempt is made to justify the categories—they serve only as an illustration of the types of needs neighborhood characteristics might be related to. Many of the descriptions could be related to more than one need category. It is particularly difficult to relate statements to the higher levels of need: esteem and self-actualization.

living in a certain neighborhood will be beneficial in a number of ways. To substantiate his claim, he appeals to some of the needs that might be satisfied if the buyer chooses to live in his property (table 1). Thus, he actively sells the neighborhood even though he may only own one or two of the residential units.

The appeal to different types of needs was recently investigated in another study in which a number of real-estate agents were asked to describe the sales tactics they would normally use in selling two identical houses in different parts of the city. The results of the study indicated that sales tactics are based, at least in part, on a subjective evaluation of how the neighborhood will cater to the needs of the potential buyer. It was interesting to note that significantly different strategies were adopted for selling urban fringe properties compared to within-city properties, a result that suggests that buyers on the urban fringe expect their house and neighborhood to cater to different types of needs, and also that sellers are able to perceive such differences in needs.

From the investigations made thus far, there is reason to believe that neighborhood is bought and sold on the basis of its contribution to the need-satisfaction of the potential residents. When we buy a property, we also get a piece of a neighborhood. We expect to like living in the neighborhood and we hope to benefit from it.

Residential neighborhoods can potentially cater to needs at many different levels. Some neighborhoods may satisfy only what Maslow called "low" level

needs such as safety and security, whereas others may also offer "higher" level need satisfaction, such as an esthetically pleasing environment and the opportunity to enhance one's individuality.

Theoretically at least, a neighborhood catering to a wide range of needs, particularly those "higher" on Maslow's heirarchy, would provide a more therapeutic and humane living environment. Unfortunately, to test such a hypothesis it would be necessary to find out whether the neighborhoods live up to the buyer's or the seller's expectations. In many cases we would find that the seller exaggerated the benefits and the buyer underestimated the shortcomings. Thus a real-estate agent might describe some neighborhood features very favorably. For example, a subdivision outside Ann Arbor might be described as ". . . a paradise somewhere west of Detroit"; and an apartment complex in Norman might feature ". . . beautiful lots—surrounded by large trees and rolling hills . . ." It is interesting how one can characterize the stunted black oaks and the flat plains of central Oklahoma! Realtors are usually skillful at turning something unpleasant into something that at least sounds tolerable. An apartment complex in Dallas, for example, at the intersection of two interstate highways, can be described as ". . . conveniently located with four-lane access in every direction . . ."

The buyer may find that the advertisements were illusions; that the neighbors are not so friendly after all; and that the view is not nearly so nice when the sun isn't shining. For reasons such as these, neighborhood selling tactics are, at best, only an approximation of the actual benefits one might find from living in a particular location. Nevertheless, they provide an informal guideline and some insight into the types of visual and functional attributes of residential neighborhoods.

VISUAL AND FUNCTIONAL COMPONENTS OF NEIGHBORHOOD: AN OBJECTIVE STUDY

Data were collected from a variety of sources to describe the visual and functional characteristics of a sample ($n = 102$) of residential neighborhoods in southeastern Michigan. It is important to point out at the outset that the visual and functional characteristics are not always entirely independent. For example, a high incidence of vehicular traffic would inhibit human functioning by preventing interaction and creating noise pollution, but at the same time the traffic would present a visual stimulus. In general, the variables were selected to describe visual and functional characteristics; in other words, they were chosen to describe (1) what could be seen in and around the neighborhood, and (2) any other features that might be related to human functioning and the satisfaction of needs in the neighborhood.

With an individual street address in the center, two data cells were constructed to represent each neighborhood. The first unit was a square cell 1,200 feet on all sides, which was intended to be a visual neighborhood, an area adjacent to the individual house and visible from the house. The size of the cell was determined in a pilot study as an average estimate of the distance visible from any given house. A larger unit, measuring 3,600 feet, was constructed to represent a largely nonvisual, but within-walking distance neighborhood surrounding the immediate neighborhood on all sides. Using these two cells, it was possible to collect data describing neighborhood character at different scales. This would be an advantage if the immediate neighborhood were not entirely representative of its surroundings. The 55 variables collected were intended to represent some of the visual and functional neighborhood characteristics for an individual residing at the center of the two data cells.

The variables were then used to identify some of the underlying characteristics of the residential neighborhoods in the sample. Using a combination of multidimensional scaling techniques described elsewhere *(Smith 1974)*, I identified 10 dimensions and named and described each one (table 2). As far as possible nonconnotative names were selected for the dimensions.

It was hypothesized that the dimensions describe at least some of the characteristics that would make a neighborhood more or less pleasant or stressful as a place to live in. To test such a hypothesis, it would be necessary to investigate a sample of individuals living in different residential neighborhoods. For every individual, scores could be assigned for each of the 10 dimensions; and those scores could subsequently be used as independent variables to predict psychological well-being.

Method

As a first step in testing this hypothesis, the dimensions have been used to investigate the effects of the residential environment on the psychological well-being of a group (n=71) of former mental patients discharged from hospitals. From the medical records and from questionnaires, it was possible to construct three surrogate measures of well-being for the former patients:

1. *Recidivism/nonrecidivism.* — Their ability to stay out of the hospital for a period of 12 months.
2. *Good adjustment/poor adjustment.* —From a follow-up questionnaire completed 3 months after release, a

Table 2.—The dimensions of residential neighborhoods

Dimension names	Items
Commercial/Industrial	Percentage of nonresidential structures
	Percentage of commercial/industrial land use
	Percentage of transportational land use
Recreational	Percentage of designated recreation
	Distance to nearest recreational facility
	Percentage of open space
Close to water	Distance to nearest water
	Percentage of cell covered by water
Arboreal	Hilliness—number of contours
	Percentage tree cover (individual trees)
	Percentage tree cover (in stands)
Low housing density	Distance between houses (side)
	Percentage of residential structures
	Space per house
	Percentage agricultural and vacant land
	Space per person
	Distance between houses (back)
	Distance between houses (front)
Black overcrowded	Percentage of black individuals
	Percentage of overcrowded units
	Percentage of female heads of household
Expensive real estate	Average unit value
	Average number of rooms per house
	Diversity of unit and street layout
Transience	Amount of through vehicular traffic
	Percentage of houses with boarders
Low unit density	Percentage of individuals over 65 years old
	Persons per unit
	Percentage of one-person units
Single-family uniform housing	Variety of residential building sizes
	Percentage of houses owned
	Variety of residential unit types
	Percentage of individuals
	Percentage of predominant land use
	Number of different land uses

composite measure of adjustment was constructed from items describing the interpersonal, social and recreational, family, employment, and community adjustment of the former patients. The mean score on this measure was used as a cut-off point.

3. *Low stress/high stress.* — Again from the follow-up questionnaire, this item was measured from the incidence and seriousness of stressful events encountered by the patients in the first 3 months after release. In a separate study a scoring mechanism was devised to assign weights to reflect the stressful nature of the different events. Again the mean score for the whole sample was used as a cut-off point. The construction of the scales was discussed in detail in Smith *(1974)*.

For each patient a profile describing his or her residential neighborhood was developed by assigning a score on each of the 10 residential dimensions described earlier. The profile was used in a discriminant analysis model to predict recidivism, adjustment, and stress in the former patients.

Prediction of Recidivism/Nonrecidivism

Scores on 3 of the 10 dimensions, Commercial/Industrial, Low Unit Density, and Transience — predicted outcome correctly for 46 (65 percent) of the 71 patients in the sample (table 3).

Although the prediction of return to the hospital is not remarkable, the results indicated that the type of neighborhood predicts correctly in nearly two out of every three cases which patients will return to the hospital. This is an interesting and encouraging finding, especially when compared to the actual rate of recidivism in the sample, which was over 50 percent. The implication, which is made extremely cautiously and perhaps even a little flippantly at this stage, is that a geographer, with information only on where in the community the patients live, can predict outcome significantly more accurately than the hospital staff.

The patient's neighborhood predicts staying out of the hospital more accurately than returning (25:10 as opposed to 21:15). One can suggest cautiously from this finding that some patients are able to compensate for, or to ignore, the negative and stressful effects of living in an unpleasant neighborhood — for example one with high scores on the Commercial/Industrial dimension or the Transience dimension. On the other hand, the positive benefits of living in a more pleasant setting appear to be substantial. The implication that the pleasant is therapeutic but that the unpleasant can be inhibited or shut-out is irresistible.

It is important to make some statement concerning the Low Unit Density

Table 3.—Residential dimensions selected to discriminate return/nonreturn to hospital

Dimension	Percent correct prediction	d^2*	f statistic	Significance
Commercial/Industrial	53.5	0.21	3.77	0.05
Low unit density	64.8	.46	3.97	.02
Transience	64.8	.65	3.71	.01

CLASSIFICATION OF RETURN/NONRETURN

	No return	*Return*	*Total*
Correct group	25	21	46
Incorrect group	10	15	25
Total	35	36	71
Correct classification	46/71=65% p>95%		

*Mahalonobis distance function—a measure of the amount of discrimination between the two groups (see *Smith 1974*).

dimension, which describes neighborhoods with a high proportion of old people and people who live alone. The discriminant model indicated, somewhat surprisingly, that the patients who lived in neighborhoods with high scores on this dimension are more likely to stay out of the hospital than patients who lived in other neighborhoods. A tentative conclusion from this finding is that loneliness and a lack of social contact are not related to recidivism and nonrecidivism in former mental patients. It is possible that neighborhoods of this type are very familiar to mental patients, and that they provide a low-key setting in which the community makes few normative demands.

Prediction of Good Adjustment/Poor Adjustment

Two dimensions — Low Housing Density and Recreational — were selected as discriminators of adjustment (table 4), but the discrimination was not significant at the 95 percent level. It is interesting to note, however, that neither of these dimensions was included as a predictor of recidivism, which indicates that adjustment and recidivism are fairly independent of one another. This finding seems, at first, a little surprising because one would expect patients who adjust poorly to return to the hospital, and vice versa. On the other hand, it may be that recidivism rates do not reflect actual adjustment in the community. Patients living with their families, for example, may live a very sheltered life. They may not be required to adjust to community life in the broadest sense, but they do not return to the hospital because their family provides the necessary support.

The Low Housing Density and Recreational dimensions predict good adjustment much more accurately than poor adjustment (20:7 as opposed to 22:22). This too would indicate that the characteristics of some neighborhoods offer a substantial positive benefit. In this case, the results suggest that spacious neighborhoods may offer more room for people to move around in, more privacy, more opportunities for recreation, and so on.

Prediction of Low Stress/High Stress

The prediction of scores on the Stress index was the highest of the three well-being measures, with four dimensions selected as significant predictors (table 5). Arboreal, Commercial/Industrial, Low Unit Density, and Transience, together predicted the stress scores accurately for 49 of the 71 patients (69 percent). Three of these dimensions are the same as those selected to predict recidivism, which indicates that stress and return to the hospital might be closely related (and conversely, low

Table 4.—Residential dimensions selected to discriminate good adjustment/poor adjustment*

Dimension	Percent correct prediction	d^2	f statistic	Significance
Low housing density	53.5	0.23	3.59	0.06
Recreational	59.2	.41	3.08	.05

CLASSIFICATION OF GOOD ADJUSTMENT/POOR ADJUSTMENT

	Good adjustment	*Poor adjustment*	*Total*
Correct group	20	22	42
Incorrect group	7	22	29
Total	27	44	71
Correct classification	42/71=59.2%	p<95%	

*The mean score was used as a cut-off point; patients with scores below the mean=good adjusters and vice versa.

Table 5.—Residential dimensions selected to discriminate low stress/high stress

Dimension	Percent correct prediction	d^2	f statistic	Significance
Arboreal	59.2	0.21	3.04	0.08
Commercial/industrial	60.6	.48	3.50	.03
Low unit density	64.8	.68	3.25	.02
Transience	69.0	.86	3.02	.02

CLASSIFICATION OF LOW STRESS/HIGH STRESS

	Low stress	*High stress*	*Total*
Correct group	20	29	49
Incorrect group	9	13	22
Total	29	42	71

Correct classification = 49/71 = 69% p>95%

stress is related to nonreturn to the hospital). It is reasonable to assume that the people who encounter a large number of stressful events and are unable to cope with these events, will be the ones most likely to return to the hospital. The inclusion of the Arboreal dimension in the overall prediction suggests that there are some positive benefits accruing to patients who live in hilly neighborhoods with tree-lined streets. Again, only a positive influence of the Arboreal dimension was detected.

For all three well-being measures, the results indicated that neighborhood characteristics predict outcome significantly in a sample of former mental patients. Some tentative explanations were provided, but one should proceed with great caution in suggesting cause and effect relationships. In another study the author has shown that the predictions made by the residential dimensions were almost as accurate as those made from a series of social and psychological variables collected in the follow-up questionnaire. In this exploratory study we concluded that the hypothesis relating the visual and functional character of residential neighborhoods to the satisfaction of human needs and psychological well-being, has been partially supported.

In ongoing work I am attempting to provide further support for the hypothesis by testing it in a normal population group.

SUMMARY AND CONCLUSIONS

The characteristics of an individual's residential neighborhood could contribute positively or negatively to his or her psychological well-being. An investigation of the advertising used to sell houses and apartments indicated that neighborhood is bought and sold at least partly on the basis of its ability to enhance the quality of life of the potential resident. To test the hypothesis, an empirical investigation was conducted, using a sample of residential neighborhoods in southeastern Michigan. Data describing the visual and functional characteristics of the neighborhoods were collapsed into 10 underlying dimensions, using a variety of multidimensional scaling techniques. With the scores on the 10 residential dimensions as independent variables, psychological well-being was predicted for a group of mental patients recently released from a large state hospital. The results showed that several of the residential dimensions could predict significantly the patients' scores on three measures of psychological well-being: recidivism, adjustment, and stress level.

Although the results should be interpreted with great caution, they at least indicate that certain neighborhood characteristics may offer a setting that is pleasing, relatively stress-free, and conducive to recuperation in former mental patients. The results suggested that positive and pleasant characteristics

provide a therapeutic environment, but in most cases unsightly and negative characteristics were shown to have only a weak influence. At this stage it is not clear to what extent these findings are applicable to a normal population group, but research in this area is being conducted. One should beware of putting too much emphasis on the findings, bearing in mind the particularly powerful arguments against making ecological inferences of this type. The results suggest certain trends in the data, but it may be unwise to go beyond the most exploratory statements.

On the other hand, this study is an encouraging start, and has moved in an intuitively satisfying direction. The results and the methodology described point to both the feasibility and the desirability of attempting to measure some of the humane dimensions in the physical world. It is to be hoped that in further studies researchers will be able to characterize more clearly those elements of the built environment that are related to the enhancement of psychological well-being and the quality of human life.

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Environmental Perceptions of Residents of a Multifunctional Building

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ABSTRACT.—A multifunctional building in which residents could live, work, and entertain themselves without contact with the surrounding external urban environment is the subject of this study. To what extent do inhabitants of this structure perceive their thermal and acoustical environments within the building to be different from or similar to that outside? To what degree are discrete climatic and sound zones perceived within the structure itself? What factors account for such perceptions? Answers to these questions were provided by an analysis of the responses by 246 residents of the John Hancock Center in Chicago to a mail questionnaire.

THE CONCEPT of a single physical structure serving a multitude of functions is not particularly new. Buildings have long existed that housed a combination of services. Any large city, for example, contains office buildings with stores on the street floor, residential structures built over shops, and hotels with both offices and stores.

These multipurpose buildings owe their existence, mostly to economic considerations. They have been developed in such a manner because it was politically and financially advantageous to do so. Usually, little attention was given to the physical needs or wants of the people who were to inhabit them.

Recently, however, we have begun to see the erection of buildings that are designed to take care of the residents' social as well as economic needs. These structures are intended to be self-contained in the sense that they provide all the services and facilities necessary to sustain life. One could live, work, and be entertained within a single building. Such structures have recently been constructed in Chicago, Minneapolis/St. Paul, and New York City.

A good example of a multipurpose building with potential for self-containment is the John Hancock Center in Chicago. Erected in 1969, this 100-story structure contains 29 floors of office space, 48 floors of apartment condominiums, and 11 floors of restaurants, lounges, and other residential and recreational services. In theory, it would be possible for residents of this condominium to lead relatively modern lives within the Center without ever coming into contact with outside people or the natural and physical environment of Chicago.

With this in mind, a study was undertaken in May 1975 to determine: (1) the degree to which the inhabitants of 175 East Delaware Place Condominium (the residential portion of the John Hancock Center) actually treated the Center as a self-contained building; and (2) how their residence in it influenced their perceptions of the environment both within and outside the John Hancock Center.

PROCEDURES

The instrument used in the study was a questionnaire mailed to a random sample of the apartments within the condominium. Ten suites on each of the 48 residential floors were surveyed. Of the 480 questionnaires distributed, 246 were returned in time to be analyzed for this study. This represents approximately one-third of the occupants of the condominium in the spring of 1975.

The questionnaire contained 10 questions. The respondent was asked to circle one of four choices given as possible answers. Judging from the relatively high rate of response for such a mail survey, the total lack of critical comments, and the rarity of unanswered questions, it can be inferred that both the questions and the answer choices were clear and readily understandable.

The first four questions were designed to obtain background information pertinent to the projected statistical analyses. They determined in what floor grouping the resident lived, the directional exposure of the apartment, how frequently the subject left the building, and his or her occupation.

The other six questions sought to ascertain the degree to which residents perceived differences in the climatic and acoustical environments present within and outside the John Hancock Center. Residents were asked how often they noticed differences between the outside climate and that within the Center, and between one area of the building and another. Similar questions were asked regarding the acoustical environment. An attempt was also made to determine whether residents tried to alter the thermal environment within their apartments.

The resulting data were subjected to three types of statistical analyses: (1) arrangement according to response percentages; (2) cross-tabulations to observe the nature of the distribution, chi-square technique being applied where appropriate; and (3) Pearson correlation coefficients to ascertain the degree of relationship between paired variables.

FINDINGS

The arrangement of the data according to response percentages yielded the following pertinent results.

1. Ninety-three percent of the residents responding indicated that they left the building at least once a day; 4 percent went outside every other day; and 1 percent left only every third day.

2. Eighty-nine percent of those replying always or sometimes observed a difference between the climate outside and that within the Center. Ten percent rarely or never did.

3. Seventy-one percent of the residents responding observed acoustical differences between the area within the Center and that outside. Twenty-nine percent rarely or never noted such differences.

4. Sixty-three percent of those responding indicated that they rarely or never sensed differences in the Center's internal climate from one area to another. Thirty-seven percent sensed climatic differences sometimes or always.

5. Sixty-eight percent of the residents replying rarely or never noted acoustical differences from one area of the Center to another. Thirty-two percent sometimes or always did.

The data responsible for these percentages were subjected to further statistical analyses to ascertain possible explanations for the perceptions revealed. These analyses yielded the following results:

6. A relationship of 17.94 with 9 degrees of freedom existed between the number of times a respondent left the Center per day and the degree of his or her perception of differences between the outside thermal environment and that within the Center.

7. A correlation of 0.21 existed between residents who perceived differences between the climate within and outside the Center and those who were sensitive to climatic zones within the structure.

8. A correlation of 0.31 existed between residents who perceived differences between the climate within and outside the Center and those who perceived acoustical differences in the same areas.

9. A correlation of 0.47 existed between residents who perceived different

climatic zones within the Center and those who sensed different acoustical areas within the building.

10. A correlation of 0.42 existed between residents who perceived differences between the acoustical environments within and outside the Center and those who sensed similar differences for acoustical zones within the structure.

11. A correlation of 0.31 existed between residents who perceived different climatic zones within the Center and those who sensed differences in the acoustical environments within and outside the Center.

CONCLUSIONS

Several conclusions seem warranted by the findings cited above.

1. Those residents responding did not choose to treat the John Hancock Center as a self-contained building. This can be seen in the overwhelming number (93 percent) of people who feel the need to leave the structure at least once each day.

In addition, the occupational breakdown of those responding indicated jobs that could be performed within the Center. Eighty-one percent of those replying classified themselves as business persons or professionals, while 14 percent said that they were housewives. Thus self-containment was a practical possibility for 95 percent of the respondents.

The most obvious explanation why these residents refused to remain in the Center for long periods of time is its placement in downtown Chicago. Because of the economic and social diversity available on the outside, the city acts like a magnet drawing the Center's inhabitants outward. It is interesting to speculate on whether the residents would behave differently if the Center were located in a medium-size city or small town.

2. Those residents responding were acutely aware of differences between the climate within and outside the Center. Eighty-nine percent of those replying always or sometimes observed such differences. This result is obviously not surprising.

However, the fact that 10 percent of the respondents rarely or never noted such differences is important. The thermal environment of the Center is an artificial one. One would expect nearly total agreement that such climatic differences always existed. The fact that this is not the case is all the more remarkable in a city like Chicago, which has a wide range in temperatures throughout the year. However, the timing of the survey may have adversely affected the results. May is a relatively temperate month, requiring little if any modification (heat/air-conditioning) of the Center's internal climate.

Nevertheless, there does seem to be some indication here that for a significant minority of Center residents the artificial environment, or the natural one, is not perceived to the degree that would be expected. This is an area in which further research is necessary.

3. A large majority of the respondents perceived acoustical differences between the environment within and outside the Center. Promotional literature for the condominium apartments stress that even the lowest ones, those on the 45th floor, are above street noises. Thus, it is not surprising that 71 percent of those replying perceived such distinct sound environments.

Yet, the fact that 29 percent of the subjects rarely or never noted such differences is remarkable. It is hard to explain how nearly one-third of the population would fail to note differences in the sound-intensity level when leaving or entering the Center, especially with its artificially-created acoustical environment. One possible explanation for the disparity between this figure and that concerned with climatic perception is that the respondents' sensitivity to acoustical differences is less well developed than their thermosensitivity.

This does little, however, to explain the inability of significant numbers of residents to perceive environmental changes.

4. A majority of the respondents did not note significant differences in the Center's internal environment from one area to another. This was true for both climatic and acoustical perceptions. Sixty-three percent and 68 percent respectively of those responding indicated that they rarely or never sensed such zones.

This conclusion is interesting in that it is difficult to believe that identical thermal and sound environments exist in every apartment, in each of the halls leading to them, in the lobby areas, in the supermarket, etc. While it is possible that the climate and acoustics within the Center are *relatively* uniform, this seems an insufficient explanation for the proportionally low level of perception.

It seems more likely that the concepts of climatic and thermal zones within a building may be such new ones that many of the respondents were not conscious of them or could not recognize them for what they were. In this sense, their thermosensitivity was in need of heightening.

5. A significant determinant of the degree of environmental perception for residents of the John Hancock Center was the frequency of trips they took outside the building. The more often a resident left the building, the more likely he or she was to perceive climatic differences between the environments within and outside the building.

It would appear that one's thermosensitivity was heightened or lowered depending on how often one left the building. If this is generally true, one might postulate that a more self-contained structure would lead to a diminution of thermosensitivity on the part of the residents. This is a point that deserves further investigation.

6. Those respondents who perceived differences between the environment within the Center and that outside also tended to be the ones who noted different environmental zones within the building. This was true for both thermal and acoustical observations. A correlation of 0.21 existed for the former and 0.42 for the latter.

These results indicate that residents sensitive to climatic or acoustical differences maintain this perception regardless of the environment in which they find themselves. In other words, the artificial environment within the Center brought out responses similar to those engendered by the natural and man-made environment of Chicago, or vice versa.

Furthermore, it seems that residents of the Center are twice as likely to have such similar perceptions in the acoustical realm as in the thermal one. Why this disparity should exist is not immediately apparent. Possibly the soundproofing of the Center is more effective than the thermal controls. This, in turn, may tend to make the residents more aware of acoustical changes. However, such a conclusion must remain tentative, pending further descriptive and statistical research.

7. The respondents who perceived thermal differences were more likely to sense acoustical differences as well, and vice versa. Thus there existed a correlation of 0.31 between residents who noted climatic *and* sound differences between the outside environment and that within the Center. Similarly, a correlation of 0.47 was found between subjects sensing discrete thermal *and* acoustical zones within the structure.

Thus it seems that thermosensitivity and audiosensitivity tend to develop together when present to a significant degree.

Why there should be a higher correlation concerning the internal environment is difficult to explain. It may be that such observations require a greater degree of perceptiveness than sensing indoor/outdoor differences, and that

when it is present it is more likely to manifest itself in all sensory areas.

This study was primarily exploratory in nature. Most of the conclusions are tentative, and they point up the need for further research in this field. In addition, the results reported were based on a general analysis of the data generated, rather than a cell-by-cell exploration. It is possible that the latter will provide additional insight into the reasons for the apparent inconsistencies noted in the conclusions above. In any case, this is an area of investigation that deserves greater attention, particularly in light of the increasing number of multifunctional buildings being constructed in the United States.

Acknowledgments. The author wishes to thank the Fordham University Research Council for financial assistance in this study. He is also indebted to Arthur P. Sullivan of Fordham University and Theodore Garofalo of the Yonkers, N. Y. public schools for their help in the compilation of the data.

Relocation within the Urban Environment

by DAVID R. DiMARTINO, *assistant professor of geography, The Ohio State University, Marion.*

ABSTRACT.—Analysis of motives indicates that minimal consideration is given to the physical environment when urban households select from among alternative residential locations. There is a greater awareness of, and response to the economic and social conditions of the residential environment among movers. When the motivations of highly-educated white-collar professionals are correlated with their household characteristics and residency experience, few variables discriminate at all between those who view the physical environment as an important motive for relocation, and those who do not. The physical environment is cited more frequently (and considered more important) during the relocation process by owners of residences, rather than renters.

INTRA-URBAN RESIDENTIAL MOBILITY, the relocation of residents within their urban environment, is a behavioral process. Movers undertake a relocation based upon the perceived needs of their households; relocations are made in order to achieve some goal, to acquire some amenity at the new residence, or to avoid disamenity at the former residence.

The mobility process operates through the appraisal of alternative residential locations by the mover; as such, the mobility process is an adaptive mechanism within the urban environment. The motivations for relocating, as expressed by the movers themselves, are the best indication of both the causes of mobility and the residents' perceptions of the urban environment.

The mobility motives of households questioned in this study yields a perception of the city as a *non*physical, socio-economic environment. The physical environment of the city is cited far less frequently as a motive for relocating, than are other social and economic considerations. And such physical environmental motives are usually couched in avoidance terms; that is, households which cite a physical environmental motive for relocating tend to seek an escape from the urban environment. Thus, not only are alternative physical environments in the city not sought, they are not perceived to exist.

RESEARCH DESIGN

Previous studies of residential mobility suggest that the rate of mobility is greater among families whose heads-of-household are highly educated and employed within white-collar professions *(Rossi 1955, Simmons 1968).* The faculty members at the State University of New York at Binghamton were selected for examination as a significantly mobile and relatively informed study group.

Faculty to be investigated were selected via a random-stratified sampling procedure. The faculty members' names were grouped by university rank, and a random sample of faculty names was selected from within each rank (using a random-number generating computer program). The random-stratified sampling insures the selection of a study group with varying incomes, ages, and household characteristics.

A personal interview was conducted with each of the faculty members sampled. Twelve percent of the faculty were interviewed; those interviewed were involved in a total of 100 residential relocations within the Triple Cities area (the Binghamton/Johnson City/

Endicott area). The data base of the study thus consisted of 100 separate moves.

The interviews solicited information concerning both the respondents' household characteristics and mobility motives for each of their moves within the Triple Cities area. The respondents were asked to explain their motives for selecting a new residential location (rather than for vacating their previous residence).

Having completely stated their mobility motives, the respondents were asked to rank their motives according to their order of importance; they were ranked as the primary, secondary, and tertiary motives for their moves. Frequency tables of the respondents' primary, secondary, tertiary, and total motives were constructed; the tables arrayed both the individual motives and groups of related motives.

The mobility motives were then scaled (individually and by groups) along a continuum of what might be described as more- to less-functional motivations (materialistic to esthetic). The motivations thus scaled were compared to the variations in the background variables such as age of head-of-household, size of household, etc. The comparison was made by using a simple nonparametric correlation technique — Cross-Tabulation (the BMDO8D program of the UCLA Biomedical Programs series).

CHARACTERISTICS OF THE SAMPLE AND THEIR RELOCATIONS

The study group consisted of a relatively mobile set of households. As highly-educated white-collar professionals they exhibited a relatively high mobility. And as relatively young married households of small size they also exhibited a mobility potential greater than the average, because they were in relatively early stages of their life-cycles *(Rossi 1955)*.

In addition, the sample households were relatively recent arrivals to the Triple Cities. Although their previous rental and ownership experience was considerable, their experience within the Triple Cities area was far less substantial. Their knowledge of the Triple Cities' residential environment, therefore, may have been incomplete; and this fact may have contributed to additional relocations within the area.

Indicative of their relatively recent arrival to the Triple Cities area, twice as many of the households utilized *non*-personal information sources for relocating (such as newspapers and realtors) as did personal information sources (such as friends and colleagues). Marrieds were particularly more dependent upon nonpersonal information sources than were singles; although the dependence upon nonpersonal sources decreased with the age of the head-of-household.

The respondents' dependence upon nonpersonal information sources was far greater than that characteristic of the more general mover population *(Rossi 1955)*. Thus, many of the mover households undertook relocations based upon information obtained from others; they made residential decisions based upon a combination of both their own and others' perceptions of the urban environment.

The information search which preceeds a mobility decision necessitates a time lag for most moves; there is time devoted to contemplating a move and time spent in searching for a new residence. Both the contemplation time and search time of the respondents in this study varied from no lag time (for spontaneous moves) to a period of 6 months. These lag times are typical of the general mover population *(Rossi 1955)*.

The respondents were atypical of the general mover population in that their contemplation and search time *increased* with the number of relocations made. Contemplation and search time usually decrease with additional relocations, be-

cause of the improved knowledge a household commands of a particular urban environment with additional mobility experience.

A possible explanation for the reversal of this relationship is that a number of respondents were changing their housing tenure status (renters becoming purchasers); the tenure change would require a different set of information for decision-making, and there would be a greater time period needed to acquire that new information.

MOBILITY MOTIVES

The motives which prompt a household to relocate within a particular urban environment yield an understanding of the causes of residential mobility; they also render a portrayal of the movers' perceptions of the urban residential environment. Examination of the mobility motives cited by the respondents of this study suggests a lesser concern with and/or perception of the physical environment, and a greater concern with the socioeconomic environment of the city.

Considerable variation existed in the individual motives cited by respondents as their reason for selecting a new residence. Several motives, however, were cited quite frequently. The five most frequently cited motives encompassed two-thirds of the total reasons and three-quarters of the primary reasons for relocating (table 1).

The single most frequently cited motive was the availability of housing; that motive was cited most frequently as both a primary and overall reason for selecting a new residential location (table 1). Cost was also frequently expressed as a motive for site selection. And, when grouped together as a category of mobility motives (table 2), the combination of availability and cost (labeled "constraints") accounted for the largest single group of both primary and total mobility motives.

While frequently cited as mobility motives, housing availability and cost are actually constraints exerted upon a household's mobility potential, rather than active causal agents of mobility. A household, for example, feels compelled to rent or purchase a residence at a cost in line with its budgetary limits; it may, however, select among a range of housing alternatives at costs equal to or less than those limits. The cost of housing thus serves as a limitation upon the range of alternatives, rather than an actual motive for relocating.

The frequency with which availability and cost are cited as reasons for relocating says much about the respondents' perceptions of the urban environment. Their frequency of citation demonstrates the respondents' perception of an extremely constricted housing market — a scarcity of housing. That perceived scarcity is relative, however; the scarcity includes housing with charac-

Table 1.—Individual mobility motives most frequently cited [Expressed as a percentage of total motives]

Motives	Motive rankings			
	Primary	Secondary	Tertiary	Total
Availability	24 (1)*	11 (3)	16 (2)	17 (1)
Cost	15 (3)	12 (2)	6 (4)	11 (4)
Age (newness)	—	—	6 (4)	—
Interior space	19 (2)	15 (1)	13 (3)	16 (2)
School district	8 (5)	10 (4)		7 (5)
Nearness to work	9 (4)	12 (2)	20 (1)	13 (3)
Summed percentages	75	60	61	64

*Order of frequency of motives within each ranking.

Table 2.—Categories of mobility motives cited [Expressed as a percentage of total motives]

Motive categories	Motive rankings			
	Primary	Secondary	Tertiary	Total
Constraints	40 (1)*	24 (2)	23 (3)	29 (1)
Structural traits	27 (2)	26 (1)	24 (2)	27 (2)
Neighborhood traits	12 (3)	19 (4)	12 (4)	14 (4)
Locational traits	10 (5)	20 (3)	29 (1)	18 (3)
Physical environmental traits	11 (4)	11 (5)	12 (4)	12 (5)

*Order of frequency of motives within each ranking.

teristics deemed necessary by the respondents, rather than a scarcity of all housing. The exact nature of the scarce characteristics is, of course, unclear.

Citing availability as a motive for the selection of a new residential site may also suggest a relatively less complete information search and/or more limited action space. These possibilities are consistent with the relatively recent arrival of many respondents to the Triple Cities area.

Aside from the motives of availability and cost, the most frequently cited motives for new site selection were: internal space (number of rooms), nearness to work place, and school district of the residence (table 1). These motives do yield information concerning the nature and location of housing preferred by the respondents; the motives, however, do not delimit any specific type of location or any specifically preferred urban environment.

A complete range of variation in the internal space of residences can be found in most housing districts of a city. Likewise, school districts, though area-specific, are usually large enough to include an ample range of housing types and residential environments. And selecting a new location close to one's workplace enables the household to choose from a range of housing types and residential environments, by virtue of the variable direction of a residence from one's workplace.

The five most frequently cited mobility motives are, thus, of minimal assistance in determining household preferences for specific urban environments. They do demonstrate the perceived needs of households and their reasons for relocating. They also yield insights into the general preferences of households for certain socioeconomic residential environments (such as type of education available for their children). But these motives yield little information concerning the preferences of the respondents for specific residential environments, particularly regarding the physical urban environment.

PHYSICAL ENVIRONMENTAL MOBILITY MOTIVES

Physical environmental concerns are cited infrequently as the mobility motives of the respondents in this study. This suggests either a lack of concern with or a lack of perception of the physical urban environment and its variations.

The individual mobility motives demonstrated a variable, though minimal, concern with the urban physical environment. The physical environmental motives involved two basic concerns: the esthetics of a residence (expressed as preferences for a view, scenery or a wooded lot), and the preference for a *non*urban, rural location. The most frequently cited single physical environmental motive was the desire for a scenic location, but that motive amounted to only 5 percent of the primary mobility motives (table 3).

When mobility motives were grouped

Table 3.—Physical environmental motives for household relocations
[Expressed as a percentage of total motives]

Motives	Motive rankings			
	Primary	Secondary	Tertiary	Total
Rural preference	5	4	2	4
Scenery	4	4	4	4
Wooded	1	0	2	1
View	0	3	3	2
Esthetic	1	0	1	1
Summed percentages	11	11	12	12

into categories (table 2), the physical environmental motives appeared as the least frequently cited category of total motives — 12 percent — and as the second-last category of primary motives cited — 11 percent. Although including a very small percentage of total and primary mobility motives, the physical environmental category did compare favorably in frequency to other categories of motives; it was comparable to neighborhood traits and locational traits among the primary motives, and to neighborhood traits among the total motives.

The physical environmental characteristics of the urban environment are, therefore, the traits deemed least significant to the relocations of the respondents in this study. And those few physical environmental traits which are considered important concern primarily the esthetics of the residential site — a subjective concern, and a concern very much in vogue at the time of this study.

The only other physical environmental concern of significance to the respondents was the preference for a *non*urban, rural residential location. That preference suggests an either/or logic in their decision-making; it demonstrates the respondents' perception of a noxious urban environment *(Wolpert 1966)* and a noxious environment of unvarying physical attributes.

The minimal expression of physical environmental motives for relocating is surprising in two respects. The respondents of this study were afforded the opportunity to cite their secondary and tertiary mobility motives, as well as their primary concern for moving; in view of that opportunity, a greater expression of physical environmental motives was expected.

In addition, the Triple Cities area extends through a quite variable physical environment; it is a riverine environment which varies widely in its range of vegetal, physiographic, and atmospheric characteristics. The respondents were thus expected to voice their preferences for residential locations within that environment.

The substantial variation in the physical attributes of the urban environment within the Triple Cities is thus of little concern to the respondents' relocations. The respondents evidence no perception of the variations in elevation, slope, insolation, humidity, pollution levels, etc. that exist among the various residential districts of the Triple Cities area.

SUMMARY AND CONCLUSIONS

The results of this study indicate the desires and perceptions of highly-educated white-collar professionals as they relocate their residences within the urban environment. These households express a range of concerns related to their mobility.

Their greatest concern in relocating is with the state of the housing market; they express a very great concern with

the availability (and cost) of housing. That dramatic concern with housing availability and cost may result from a disparity between their perceived needs and their budgetary limitations; they may see themselves as belonging within certain residential districts (by virtue of the socioeconomic status of their profession), but may be unable to afford residences within those districts (because of their recent arrival to their profession with attendent starting salaries). Thus, their concern over housing availability may suggest a self-imposed constraint as the result of their stereotypical perceptions.

The mobility motives of the respondents also demonstrate their primary concern (aside from availability and cost) with the new residence itself and additional concern with other residential characteristics of relatively limited spatial extent. While neighborhood traits are cited as motives for the selection of new residential sites, those traits involve the evaluation of primarily adjacent properties together with the school system available — both concerns of relatively limited spatial dimensions. And, while relative location is cited as another motive for relocating, that concern involves the reduction of distance and travel time from the home to other locations — a concern intended to limit contacts away from the residential district. Thus there appears to be a decreasing importance attached to mobility motives as the spatial expression of those concerns increases — a decreasing importance from residence traits to neighborhood traits to concerns with some larger urban district.

The physical environmental motives expressed by the respondents of this study are also concerns of limited spatial extent. Aside from the desire for *non*-urban residential locations, the physical environmental motives focus upon the esthetics of the residential site itself — the vegetal cover, the outward view, etc. And, while purchasers tend to mention site esthetics and rural preferences for relocating more than do renters, neither group of residents expresses a preference for the alternative physical environments existent with in the Triple Cities area.

These findings suggest a lack of concern with the physical environmental characteristics which vary across the Triple Cities area: variations in such things as pollution levels, insolation, physiography, etc. That lack of concern may reflect a sincere feeling that physical environmental characteristics are of secondary importance to the relocation process; socioeconomic characteristics may be considered of greater importance. Alternatively, the movers may not perceive the urban environment as physically variable; urban residents may view the urban physical environment as spatially homogeneous.

Whichever the case, the results are the same. The urban physical environment *is* spatially variable, and that variability *should* be of concern to urban residents. Pollution levels, flood hazards, and a multitude of other physical environmental conditions all vary with the location of a residence within its urban environment; an understanding of that fact is basic to the health and safety of urban residents.

The findings of this study, therefore, point out the need for a greater educational effort by environmentalists (and others) aimed at urban residents. Whether urban residents remain unaware of the physical variations in the urban environment, or whether they are aware but unconcerned, the knowledge of the importance of those variations must be delivered to them. The improved knowledge that now exists concerning the spatial variations existent within urban physical environments is useless unless that knowledge is lent to all those who reside within that environment.

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Residential Settings: Effects of Home and Neighborhood on the Quality of Life for Old People

by JOEY EDWARDH, *Department of Geography, Syracuse University, Syracuse, N. Y.*

ABSTRACT.—The author discusses the role of home and neighborhood in the lives of old people and explores the impact of the physical and social organization of these spaces on an old person's perception of his immediate environment and his subsequent activity patterns. Home and neighborhood reinforce an old person's sense of identity and mediate between the old person and the larger society. Information about the meaning of home and neighborhood in the lives of old people contributes to the data available to those making the decisions that affect the distribution of social and physical resources in our cities.

THE ROLES OF HOME and neighborhood in the lives of people 65 years or older were studied in two very different urban environments in Syracuse, New York. The two environments will be called *Inner City* and *Northside*. The discussion is based on 60 interviews of approximately 2 hours length and work throughout the past 2 years with an old-peoples' advocacy group.

PHYSICAL AND SOCIAL ORGANIZATION OF THE STUDY AREAS

The Inner-City study area, historically a working-class neighborhood, is located close to the high-rent central business district, near the transportation hub of Syracuse. The Inner City is heterogeneous in character, with bar-restaurants, a large number of garage and collision-repair shops, and small corner grocery and variety stores (fig. 1). Many of the garage and collision repair shops are tucked away in the backyards of old houses. In addition to the small corner grocery stores, two large supermarkets are located at opposite ends of the area. A number of unkempt lots scattered throughout the area have become graveyards for wrecked cars and discarded appliances. Large industrial structures are located close to a variety of housing — small workingmen's cottages, tenement buildings, large single-family homes converted to apartments or boarding houses, and a low-income housing project.

The Northside area is a residential area located on the periphery of the city close to suburban shopping centers. It is a homogeneous residential area characterized by small single-family frame homes surrounded by spacious yards meticulously manicured (fig. 2). The homes are located on quiet streets off two major urban arteries, which provide easy access to other sections of the city. In addition, there are two local shopping centers.

A demographic profile of the Inner City and Northside study areas is summarized below:

- The mean age (72 years) is the same in both areas.
- The ethnic character of the Northside is predominantly German, with a considerable number of Italian and Irish families. Within the Inner City the sample is ethnically more mixed, with no dominant ethnic group.
- Catholicism is the preponderant religion of those in the total sample.
- Most of those residing on the Northside live with their spouses. Most of those in the Inner City are widowed.

Figure 1.—Map of Inner City land use.

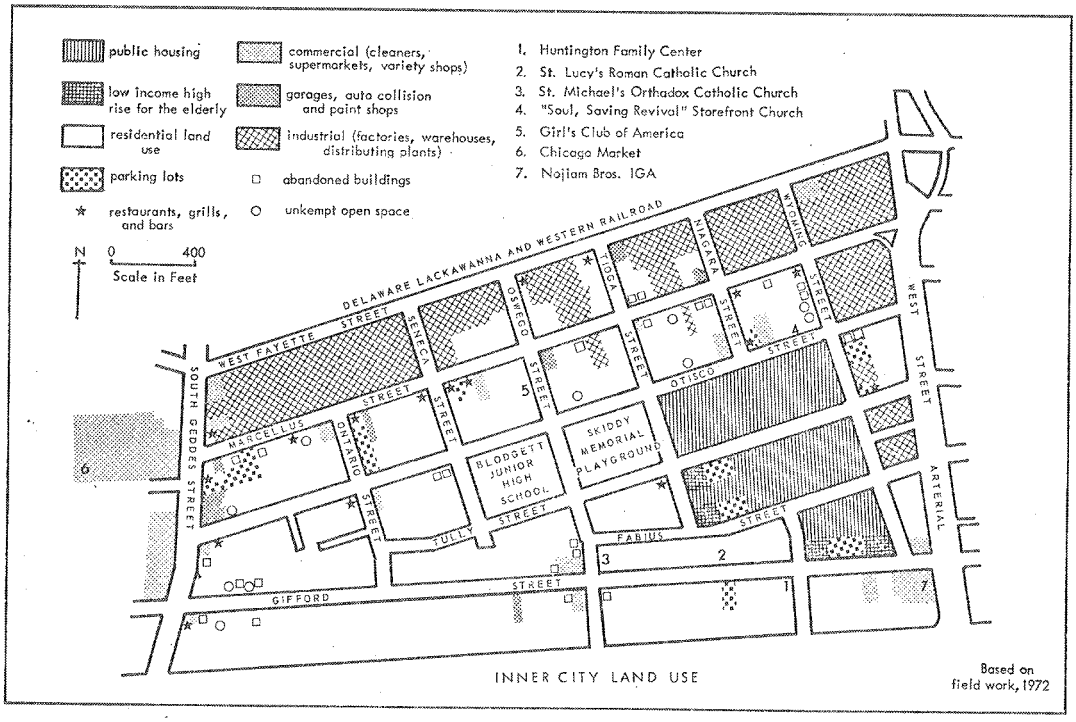
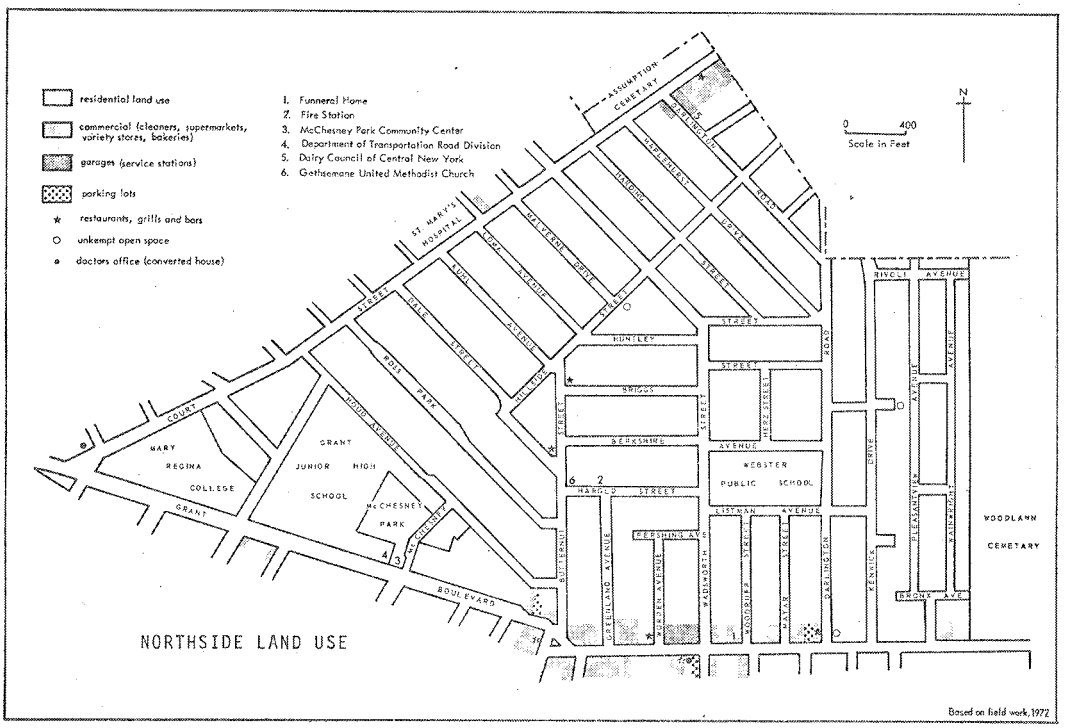


Figure 2.—Map of Northside land use.



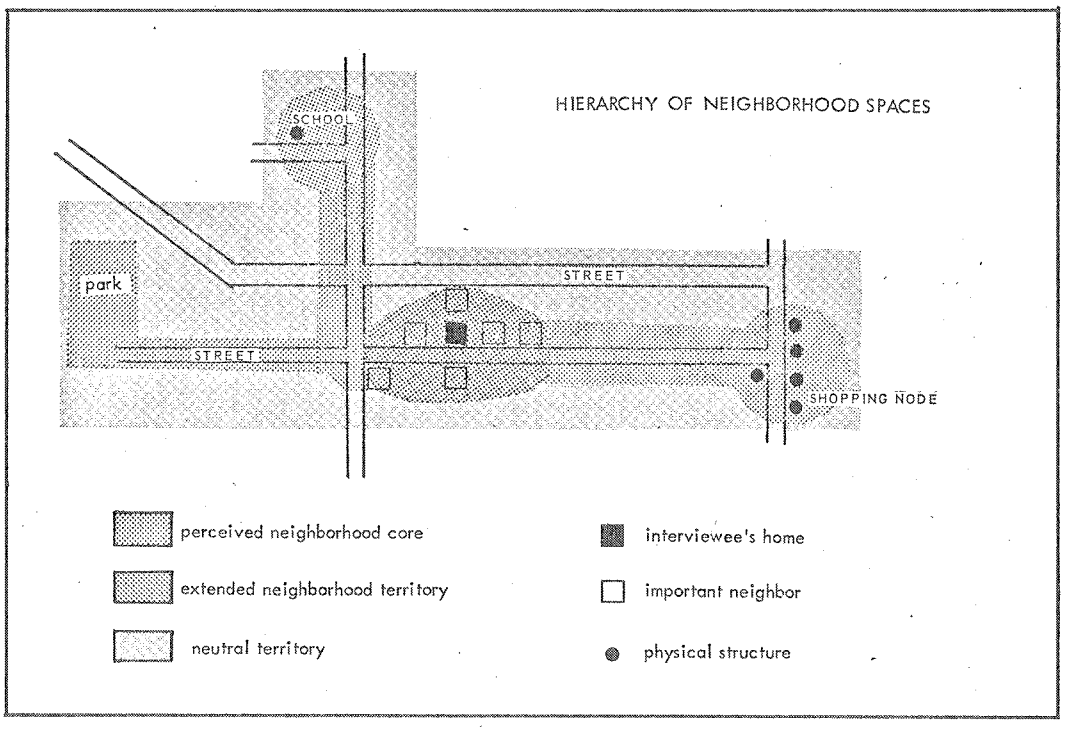
- Far more old people on the Northside have children than those living in the Inner City.
- More Inner City residents have physical disabilities.
- Years of schooling tend to be greater on the Northside, where approximately half of the residents have attended high school.
- Men in the sample population are retired blue collar workers. Most of the women in both areas who worked did so out of economic necessity.
- Residents of the two areas differed in financial status. Eighty percent of the Inner City elderly reported incomes below $3,000 as compared to 28 percent for the Northside. Most of those with incomes below $3,000 were single or widowed, and almost all of them were women. Most individuals in this income category have an annual income of approximately $1,500.

CONCEPTS OF NEIGHBORHOOD SPACE

The concept of neighborhood space is composed of two inherent ideas: proximate physical space and prescribed social interaction. An impression of the meaning of neighborhood to older respondents emerged from my interviews, the informal discussion, and field observations. The elderly perceived their neighborhood in terms of a hierarchy of spaces: home space, neighborhood core, extended neighborhood territory, and neutral territory on the periphery of the neighborhood (fig. 3). The concept of neighborhood is idiosyncratic in that each person has a different perception of his neighborhood space. Most often neighborhood space is perceived as both face sides of an average city block. Social communication and interaction occur in the neighborhood core that is close to the home.

In single-family residential sections

Figure 3.—Hierarchy of neighborhood spaces.



such as the Northside, the neighborhood core incorporates the people living next door, those directly across the street, and perhaps a few residing several houses away on the same street. Where fences and trees do not inhibit interaction with neighbors on the border of one's own backyard, this backyard territory is perceived as part of the neighborhood core. Services such as schools that the elderly's children attended, churches, small grocery stores, restaurants, and variety shops are encompassed in the extended neighborhood territory. The older person reaches these facilities by traversing a path from his home space through familiar and friendly territory to his place of destination. The elderly individual may stroll with confidence and ease both through his extended neighborhood territory and the neutral territory on the periphery of his neighborhood.

Similar concepts describe neighborhood space in the Inner City. Here factories, warehouses, parking lots, and public housing are interspersed throughout the environment. Usually these structures are not considered a part of an individual's neighborhood. For example, a number of individuals excluded from their perception of neighborhood those factories located across the street from their homes.

The presence of age-segregated high-rise housing in the Inner City makes analysis of this area complex. The elderly in public housing tend to define their neighborhood in terms of their building. Their home space is the apartment, and their neighborhood core consists mainly of those apartments on the same floor and the common lounge. An elderly woman suggested that the building is a complete spatially contained environment where the elderly "are well taken care of . . . in the building we have everything."

The interviews suggested a number of reasons for this definition. Many of those in the public housing were new to the area and were uncomfortable outside the building. Age-segregated housing provides a multiplicity of services from laundry machines, Wednesday night bingo, to across-the-hall neighbors. This has made interaction with the neighborhood outside the building unnecessary. In addition, a number of those in the housing have poor health and were classified as severely restricted or housebound. Their limited mobility prescribes that their domain of interaction be inside the building.

HOME SPACE

Home space is an individual's personal territory. It is a bounded space, a place of privacy, a place to be oneself, a place where an individual can imprint his life experience and regulate his social interaction. It is that place where memory, special objects, and loved ones are physically or at least psychologically near.

Older people on the Northside were proud of their homes and wished to remain in them. The family throughout time embellishes the home with photographs, handicrafts, and other meaningful objects. Having a place where one's children and grandchildren can return provides some incentive to continue residing in the family home. Seventy-seven percent of the Northside respondents were satisfied with the present design of their home space. The only criticism articulated was a desire that everything be located on one level. As a person gets older, it becomes more difficult to climb up or down stairs. Although some believed that their home is too large for their current needs, others have used this space for their hobbies.

Work in gardens keeps older people outside and occupies much of their leisure time. Gardening also has a social dimension. While working in their gardens, people see their neighbors and can converse with them without being obligated to entertain them.

Only 21 percent of the Inner City respondents own their homes. Comments from this group suggested that they value their home space — the privacy, the garden — in the same manner as those on the Northside. However, notably absent from their remarks is the desire to maintain the home to accommodate family visits. An interview with a widow who lives alone illustrated the complexity of home ownership and home space in the Inner City. She had just sold her home, a large structure the front half of which is a vacant store front. This structure is a remnant of past days, where she, together with her now deceased husband, operated a small variety store. Her meticulously cared for apartment is in the back of the building. She talks freely about her reasons for selling and her present apprehensions. Her annual income of $2,500 left little money for taxes and the cost of house maintenance. Moreover, she describes her physical condition as "unsteady . . . I seem to want to do nothing . . . I have to expect this because of old age . . . it's hard for me to understand for I used to work so hard . . . I had such ambition." She stated her fears: "I dread looking for a new apartment . . . here is so near the drugstore and grocery store . . . I am afraid to move because I leave my memories . . ."

Her home, along with that of many others, is an artifact that symbolizes the link between present and past time and experience. Although most respondents want to remain in their own homes as long as possible, there is a threshold when they can no longer meet the demands resulting from diminishing financial and physical resources. At this point, the older person must look for a new residence to transform into a home.

Though most (79 percent) of the Inner City elderly are renters, they take pride in maintaining and organizing their apartments to express their own personalities. Financial limitations have restricted their housing choice to the Inner City. Nonetheless the interviewees, both in the neighborhood and in the age-segregated housing, cherish the privacy offered by their own apartments or home space. Many of the Inner City residents mentioned the lack of an outside space to garden or sit out in and talk with their neighbors.

PERCEPTIONS OF NEIGHBORHOODS BY OLD RESIDENTS

On the Northside, the general consensus was that the neighborhood was ideal for senior citizens. It is conveniently located, and small stores are within easy walking distance. In addition, it is near a large suburban shopping center. The response of one elderly couple describes the sentiments of many Northside residents. It is a "good place to live, quiet and clean with large lawns for garden work that appeals to senior citizens."

In the Inner City, the sentiments expressed were, most often, the antithesis of those expressed on the Northside. When asked if this neighborhood was a good place for senior citizens to live, one elderly man's simple statement, "No, it's not good for old people . . . it is dirty, noisy, and dangerous," reflects the thoughts of many. While they may not like their neighborhood, the majority find it conveniently located with easy access to basic services such as dry-cleaning, grocery and variety stores, banks, and a post office.

A crucial component of the elderly's relationship to their neighborhood is their perception of their environment, which translates into both constraints and opportunities that influence the quality of their life. Forty-three percent of the Northside's interviewees and 83 percent of the Inner City's were afraid to leave their homes after dark. Regardless of area, single and widowed respondents were not at all inclined to be outside after dark.

Very often the residents of the Northside felt insecure about activities that

removed them from their homes at night, although few could cite any actual incident that had occurred within their neighborhood. There were those on the Northside who perceived the situation as more dangerous. One widow had so internalized her fear that she does not "dare sit out on the porch at night . . . I bolt the attic door and basement door at night . . . I am all closed up tight and don't even look out." There is little doubt that the mass media have increased the awareness of the Northside elderly concerning their personal vulnerability to the point where they, particularly widows, have altered both their perception of their environment and their behavior patterns.

The unequivocal response of the Inner City elderly was simply expressed by the statement, "You don't dare go out at night." Regret about this constraint was accompanied by the concession that in this neighborhood "years ago it was never like this — people could walk anywhere." Many of the elderly, through their neighborhood acquaintanceship networks, know of individuals who have been the victim of robberies, muggings, and rape. The presence of personal violence in their experiential world, along with the mass media emphasis on violence, engender and maintain a level of fear that ultimately inhibits any interaction outside of the home after dark.

But mobility at night is not the only time caution is exercised. The elderly, particularly women, are very concerned about themselves as easy daytime targets for purse-snatchers. A few had decided not to carry a purse when going out. Data from the Syracuse Police Department illustrating the distribution of burglaries, robberies, and public intoxication arrests in Syracuse suggest that the fears of Inner City residents are well founded.

In the Inner City, competition with other groups for the use of spaces and paths has usually meant that the elderly have retreated. For example, the location of the public housing for the elderly next to public housing for low-income families places two different groups — white elderly and black children — in spatial proximity. Competition for the use of public spaces, in this case sidewalks, ensues. As one elderly man exclaimed, "You can't walk around here; and if you try, the next thing that happens, some kid knocks you over with his bike." He, along with many others, moves slowly with care and is unable to easily get out of the way of a rapidly approaching bicycle.

The situation is exacerbated by verbal abuse from children and teenagers. Old people are the victims of name-calling and other verbal insults. Moreover, fear that the verbal assault may culminate in a physical act inhibits many elderly from criticizing or chastising the youth. They are aware that others, particularly old people, have been the victims of malicious damage such as rocks being thrown through windows.

All the public housing residents appreciate the material comforts and security afforded by residence in the building. Neat, efficient apartments, a garbage incinerator chute on each floor, and laundry facilities in the basement were the most popular benefits lauded. While proudly showing her apartment, one woman exclaimed "There are no leaks or roaches here . . . I waited three years to get an apartment . . . where else could I go? Where could I get an apartment like this for sixty-five dollars a month . . . it has a bathroom, good heat, three clothes presses."

Everyone was aware they could not possibly purchase similar accommodations on the open housing market. Though none wished to leave the housing, occasionally residents expressed a desire to relocate to newly constructed housing in more familiar neighborhoods.

It is not to be construed from these comments that public housing is the best solution to the housing needs of older people. Quite to the contrary, the move

to public housing was the only alternative for these elderly. Once in the housing, a new definition of self and a reconstitution of one's social world occurs. It is my impression that the older people were grateful to have decent housing at a cost of 25 percent of their monthly income. This housing was viewed by the old respondents as a municipal gift rather than a right.

However, there is a pervasive fear that clouds life in the public housing. Because many residents lacked information about their rights as tenants in public housing, they feared that future investigations into their personal finances might lead to an increase in rent or a termination of lease. People were worried about fluctuating income ceilings and their possible effect on them. Furthermore, they were cautious in their criticism of housing authority policies, as few knew what the repercussion might be. No one mentioned the existence of any mechanism for tenants to discuss their problems with the housing officials. As one woman concluded, "the housing authority don't care what we want."

Northside residents were more satisfied with the noise level and cleanliness and condition of sidewalks than were Inner City residents (table I).

Noise pollution means that those in the Inner City awake early in the morning to the noise of food processers dispatching their trucks. Throughout the day and night, traffic noise from horns, screeching tires, and big trucks is omnipresent, because streets in this area are principal routes for the dispersion of goods throughout the city. The local bars are social nodes for others during the night hours; but for the elderly, the noise and general rowdiness prevent sleep and increase insecurity.

Environmental cleanliness distinguishes the Northside. A major disadvantage of the Inner City's mixed land use was illustrated by one man's statement: "Papers blow into my yard from the magazine plant across the street, and by the time I pick them up the yard is covered again." For the elderly, the decline in cleanliness and corresponding visual blight is shown not only by unkempt yards, unpainted houses, junk cars, and appliances, but also by garbage and containers strewn along the sidewalks.

The elderly are one of the few groups in our automobile society that use and need sidewalks. On a pleasant day, sidewalks are the paths accommodating those walking for pleasure and exercise. Furthermore, the majority of the elderly use public transportation, and to do so must use sidewalks to get to a bus stop.

Table I.—Satisfaction with neighborhood environmental quality

Characteristics	Northside			Inner City			**
	n*	Satisfied		n	Satisfied		α
	No.	*No.*	*Pct.*	*No.*	*No.*	*Pct.*	
Clean air	30	19	63.3	30	18	60.0	0.60
Number of trees	30	23	76.7	30	20	66.7	.20
Open space	30	27	90.0	30	22	73.3	.20
Curb height	26	22	84.6	30	20	66.7	.40
Noise level	30	17	56.7	30	8	26.7	.05
Snow shoveled	29	9	31.0	30	10	31.3	.95
Cleanliness	30	27	90.0	30	16	53.5	.01
Bus stop location	30	26	86.7	30	21	70.0	.02
Sidewalk condition	28	14	50.0	30	7	23.3	.10

*Number of people responding to each question.
**The chi square coefficient is used to determine whether the difference between areas was statistically significant. The 0.05 level was used to determine statistical significance.

Consequently, when sidewalks are missing, uneven, and severly cracked, older people have difficulty.

On the Northside, the major source of dissatisfaction was the absence of sidewalks along many of blocks, which forces people to fend for themselves on the roads. On the other hand, complaints from residents of the Inner City focused on deteriorating sidewalks. A number of individuals, afraid they might fall, refused to go out walking.

Poor sidewalk maintenance is worse in the winter. Only one-third of the interviewees were satisfied with snow removal from sidewalks in their neighborhoods. Most felt that they had no safe place to walk and often found themselves remaining indoors until some of the snow melted. For many, the winter means long and lonely days stretching into lonelier nights. Most important, access to public transportation becomes difficult. The snow removed from the streets is piled on the street corners, where it freezes into huge icy mounds that people must crawl over to reach the bus.

The majority of interviewees in both areas were satisfied with the location of bus stops. However, those on the Northside were more satisfied than those in the Inner City. Research in each area indicated that bus stops are distributed with regularity throughout each area. The disparity in response might be explained partly by the concept of psychological distance. The greater vulnerability of the elderly in the Inner City engenders anxiety and alters an individual's perception of the distance to the bus stop.

In both areas, the respondents did not say that they should have a right to clean air, trees, and open space. The concept of a public right to basic physical amenities is subordinated to the American value that promotes the notion that access to these amenities is assured through private ownership. Those without sufficient resources to purchase access to these basic physical amenities must go without.

NEIGHBORING

Neighboring has been broadly defined "as any interaction with people defined as neighbors". Those interviewed had no difficulty distinguishing between neighbors and family or friends. While neighbors can become friends or family can be neighbors, the spatially controlled term neighbor is applied to anyone who shares an individual's immediate urban space. In both the Northside and Inner City, almost everyone chats informally with neighbors; however, few attend neighborhood meetings or go to dinner or a movie with a neighbor. A considerable number of Northside elderly chat over coffee in a neighbor's home, but few engage in this social activity in the Inner City. When asked if they generally know when their neighbors are home, 93 percent of those on the Northside said yes, compared to 37 percent in the Inner City. Most important, all Northside residents and 77 percent of the Inner City elderly feel that they could depend on their neighbors for help. During an emergency their neighbors would call a doctor, their children, an ambulance, or take them to a hospital. No one expects a neighbor to help care for them during an illness.

On the Northside, all entered the area as home owners, and it was understood that all should maintain their homes and yards to prevent depreciation in property values. Over the years, this commitment has worked to minimize hostilities due to proximity. The subtle consensus that a good neighbor is one who maintains his propery puts pressure on all neighbors to fulfill this unwritten obligation. A sense of belonging reinforces those who fulfill this concept of good neighbor.

This philosophy is complemented by courteous interaction where "neighbors keep track of one another . . . when you need them, they are there." Yet time changes these patterns. According to an

old woman, most of the elderly on her block have died or moved to special facilities. Their homes have been purchased by younger families who "are less friendly so I stay to myself". Furthermore, Northside neighboring has a seasonal dimension. People see and chat with their neighbors more often during the summer months, which brings people outside into their gardens.

The character of the Inner City is different from that of the Northside. As a result, it is not surprising that there are different patterns of neighboring. The transience of a renter population and the morphology of this urban area discourage those aspects of neighboring engendered by familiarity such as chatting with a neighbor in his home, knowing if your neighbor is home, and feeling you can rely on your neighbor for help.

A number of processes were operating that had contributed to the breakdown of neighborliness and neighborhood discipline. Most of the elderly considered the neighborhood to be in a state of decline from its previous status as a prosperous working class area. An elderly widow mentioned that across the street she no longer "knows anyone because people move in and out and no one takes care of the property". "The neighborhood is becoming run down", according to one elderly gentleman, since not only were "houses deteriorating" but also "many places were closed down — small businesses come and go and companies located next to the area were closed". Other racial groups are locating in the area, particularly Blacks, Puerto Ricans, and native Americans. The influx of these new neighbors has created hostility and fear.

In many cases, neighboring in the Inner City is in the form of a service where those less able are helped to get to basic services such as grocery stores. Twenty-eight percent of the Inner City elderly are completely dependent on neighbors and friends for assistance during an illness. Neighbors perform tasks such as reading mail to the blind or doing laundry for someone ill. Occasionally, expenses are shared. For example, a gentleman wanted to read both Syracuse daily newspapers but could afford only one of them; so he purchases one, his neighbor the other, and they exchange them.

All of the elderly living in the age-segregated public housing said that they could depend on their neighbors for help. For those in public housing this sentiment engendered a sense of security — there was someone to help them if they needed it. If an individual does not come to pick up his mail or visit the common lounge, someone will eventually check up on him. Interaction with one's neighbors occurs at important nodes throughout the building, particularly at the mail boxes, floor incinerator chutes, and lounge, and on the benches outside the front door. It was explained that people usually did not interrupt individuals in their apartments since they may be resting or eating, or just want to be alone. However, there are some who resent the omnipresent gossip network and consequently have curtailed their participation in any activities within the building.

CONCLUSION

Home and neighborhood are important spaces to older people since they reinforce one's sense of identity and mediate between the old person and the larger society. Home and neighborhood also help create continuity and coherence within the self.

However, the ultimate condition of old people in our society has little to do with their immediate physical and social space. Old people are the victims of a socioeconomic system that has no place for them. They no longer participate in the work force and consequently are not rewarded with material benefits. They are beyond the arbitrarily defined working years and are thought to be of little economic value and, as a result, of little

social value. A social mythology cultivating youthfulness and deploring aging allows Americans to ignore those who have contributed to the productivity of this nation throughout their working lives. Reduced to poverty, old people have no resources to explore opportunities and choose alternatives that would facilitate their adjustment to old age. It is difficult for most to purchase the necessities of life such as adequate food, clothing, shelter, health care, transportation, and recreation.

Behavorial Significance of Milieu: a Consideration of Two Downtown Settings

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ABSTRACT.—Behavior patterns in parks and plazas in downtown Syracuse, New York, are discussed. After an introduction of the spaces and their principal users, fundamental concepts borrowed from ecological psychology are defined. Then using these concepts, the behavioral significance of the environment is illustrated in a comparison of two case studies. The concepts employed here are shown to allow a discussion of the important effect of environment on behavior without producing deterministic distortions.

THE OBJECTIVES of this exploratory research were to investigate (1) who was using parks and plazas in downtown Syracuse, New York; (2) whether behavior patterns were discernible in these spaces; and (3) the ways in which physical and social factors influence these patterns.

We soon discovered that distinct user groups and behavior patterns could be identified, and our attention then became focused on the ways in which social and physical factors work together to shape these behavior patterns. In considering our preliminary results, we found that some fundamental concepts taken from Barker's theory of behavior settings *(Barker 1968)* provided a very useful framework for interpretation. After setting the context and defining these concepts, we will discuss two case studies that illustrate some of the mechanisms relating behavior patterns and physical environments.

THE CONTEXT

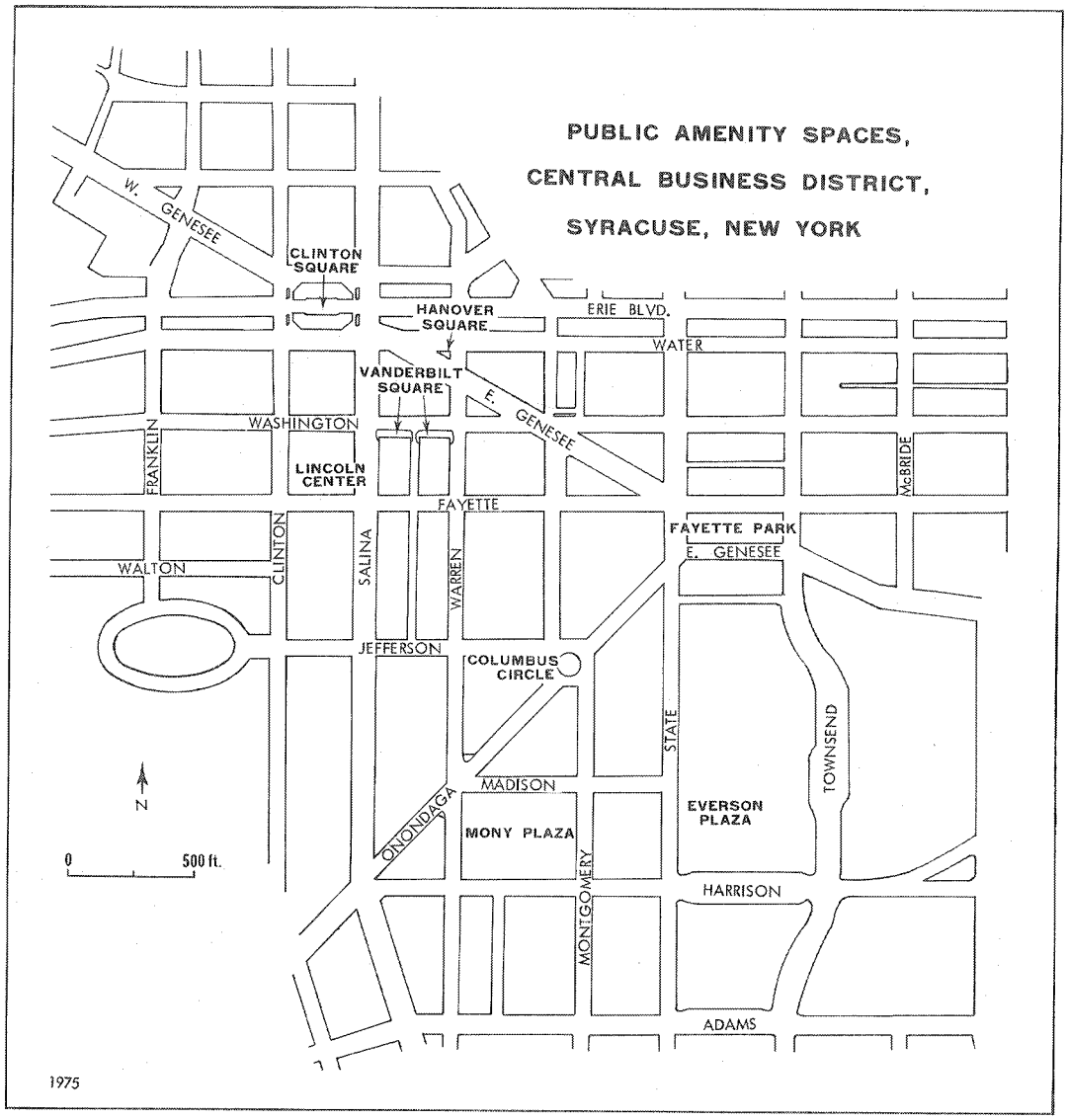
For two summers (1974 and 1975), outdoor amenity spaces in downtown Syracuse were studied. In many respects, Syracuse is a typical medium-size city (population, city limits: 157,000; Standard Metropolitan Statistical Area: 637,000). It is undergoing the same demographic and economic changes as most other American cities: residential movement to the suburbs is leaving a deteriorating central city and an ailing Central Business District (CBD). A keen interest in CBD amenity spaces is one expression of a campaign by city officials, businessmen, and assorted Syracuse enthusiasts to revitalize the downtown.

The set of outdoor amenity spaces investigated for this study included (fig. 1): (1) two commonly recognized loci of downtown social activity, Columbus Circle and Clinton Square; (2) one space dominated by urban drifters and derelicts, Hanover Square; (3) one space used primarily by retired men, Vanderbilt Square; (4) two spaces associated with large new offices buildings, MONY Plaza and Lincoln Center; and (5) two large but little used spaces, Everson Plaza and Fayette Park.

For this whole set of spaces, five major user groups can be identified in terms of their influence on daytime behavior patterns:

1. *Female office workers.* — This group consists mostly of single females

Figure 1.—Parks and plazas studied in downtown Syracuse.



between the ages of 18 and 30 engaged in clerical work downtown (secretaries, file clerks, key punch operators).

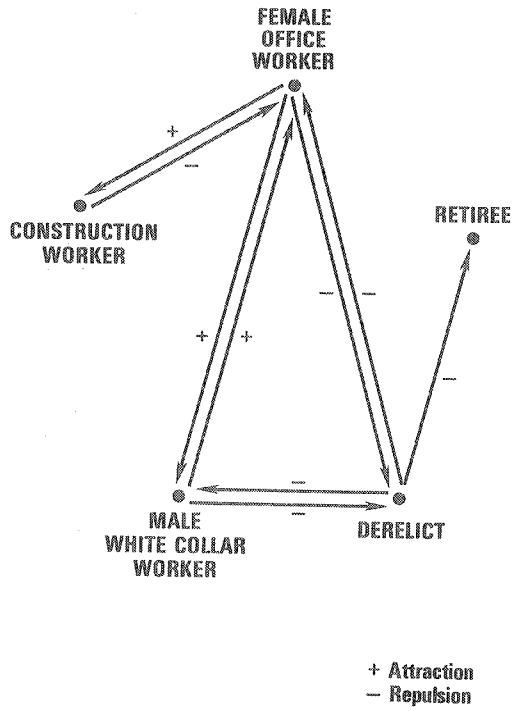
2. *Male white-collar workers.*—These men are mostly between the ages of 18 and 30 and are employed in sales, administration, and professional occupations.

3. *Construction workers.* — As the CBD undergoes physical transformation, these men are employed to demolish old structures and build new ones. Their labor is of both the unskilled and skilled varieties. In age range, they are similar to the male white-collar workers.

4. *Male retirees.* — These elderly men regularly venture downtown to meet with their cohorts for a day of reading and conversation.

5. *Derelicts.* — Mostly between the ages of 30 and 50, at least half of these men are obvious alcoholics. Many of them panhandle throughout the downtown, but use Hanover Square (for decades called "Hangover Square") as their home base.

Figure 2.—Relationships between user groups in downtown parks and plazas.



Interaction between these groups is important to the behavioral fabric of the downtown. Our observations suggest linkages of attraction and repulsion (fig. 2). It should be noted that these relationships are simple abstractions that refer to how two groups will interrelate in the absence of other groups. These basic relationships, however, can be altered under various circumstances such as the presence of other groups. For example, derelicts will be less threatening to female office workers when male white-collar workers are present.

BEHAVIOR SETTINGS

From Barker's ecological psychology, we have drawn a set of concepts that allows us to discuss the significance of environment to behavior without implying rigid deterministic causality. We have found these concepts very useful for our work in Syracuse and are convinced that they have value for other social scientists and designers interested in environment and behavior.

The grand concept of ecological psychology is the "behavior setting" *(Barker 1968:18-34)*. This is a behavioral unit that refers to an enduring pattern of behaviors situated in time and space. A university class meeting is a good example of a behavior setting: a variety of role interactions (professor, student, man, woman) produce an overall pattern of behavior that has a definite bounded location (a classroom) and a definite beginning and end (the class hour). It is important to recognize that a behavior setting is behavior, space, and time—all three as equal elements—in interrelationship.

The behavioral component of a behavior setting is called the "standing pattern of behavior". These are behavior patterns of people en masse, which are set in a particular time and place. For example, in downtown parks we found standing patterns of behavior that appeared and disappeared with the lunch hour. Individuals would enter and leave these patterns freely; yet the patterns would persist throughout the lunch hour, day to day, week to week. Standing patterns of behavior do not depend on the particular individuals involved.

The "milieu" is the "objective" component of a behavior setting. The spatial and temporal ambience of behavior, existing independently of anyone's perception of it, constitutes the milieu. The major features of the milieus we studied were the individual morphologies of the downtown amenity spaces and the hours between 11:30 a.m. and 1:30 p.m. on summer weekdays.

In a behavior setting, the behavior and milieu are said to be "synomorphic." This simply means that the behavior and its spatial and temporal ambience are

somehow compatible. For example, one does not go to a downtown plaza to practice belly dancing; it hardly seems like the appropriate environment. We will explore some of the mechanisms involved in synomorphism in more detail later.

Behavior-milieu units are called "synomorphs." With this term, a much needed word is added to the vocabulary of the environmental designer and researcher. Synomorphs are not behavior alone, nor milieu alone; they are behavior, space, and time, all together in a single unit.

Behavior settings are *sets* of synomorphs. For example, the standing patterns of behavior *and* the space and time of downtown parks during summer weekday lunch hours are behavior settings. Some of these behavior settings comprise a single synomorph, while others, because of spatial divisions within the space, include several synomorphs.

For a variety of reasons, ecological psychology is certainly *not* the final word in behavioral research: much of Barker's work introduces a precision that obscures rather than illuminates. But, even so, we find that the concepts just defined allow a useful perspective for discussions of environment and behavior. The following case studies will serve to demonstrate.

CASE STUDIES

This discussion of the lunchtime behavior settings in Columbus Circle and Clinton Square illustrates some of the mechanisms — both social and physical — involved with synomorphism. For those interested in behavior — especially for designers — this is a vitally important issue since the significance of the relationship of behavior and its context is affirmed repeatedly. The designer must be sensitive to the mechanisms involved in synomorphism. His charge is to produce particular kinds of behavior settings, not simply to add artifacts to the landscape. The empirical record for this point has been neglected by ecological psychologists, and we hope, with these brief case studies, to begin to remedy this deficiency.

Columbus Circle and Clinton Square share many characteristics: they are the two most commonly recognized CBD parks; each has historical significance; they are both large and centrally located; each is a major pedestrian intersection; all the major user groups have access to each space; each has a similarly large number of potential users; and both provide a pleasant esthetic experience. In spite of these similarities, however, the standing patterns of behavior for each setting are clearly different. The festive behavior setting in Columbus Circle is in striking contrast to the subdued setting in Clinton Square. The milieu for each setting is also clearly different. Consistent with the principle of behavior-milieu synomorphism, behavioral differences can be largely understood by examining milieu differences.

Columbus Circle

Columbus Circle is a relatively large park located in the southern part of the CBD (fig. 1 and 3). It is snugly situated in the midst of mostly municipal and religious buildings: the Public Library to the north, the County Courthouse to the east, a Catholic cathedral to the west, and, on the south, a six-story office building. At one time a small traffic rotary, the western half of the Circle was recently connected to the front of the cathedral, and walking and sitting areas were developed around the fountain. Still a major pedestrian intersection, Columbus Circle is now the most heavily used park in the CBD; during the summer an average of about 80 people will congregate there at lunchtime.

Observation has shown that, in terms of the proportion of the total lunchtime user population, three groups dominate

Figure 3.—Columbus Circle, looking west. This photograph, taken in the spring, shows Columbus Circle still packed up for the winter; during the summer, benches are moved from the center of the cluster, and the fountain is in operation.



in Columbus Circle: female office workers, male white-collar workers, and construction workers. The standing pattern of behavior is heavily influenced by the interaction of these three groups.

Several types of behavior are common in the standing pattern: people watching, sunning, socializing, "hanging out" (waiting for unarranged gatherings to materialize), and, of course, eating. Columbus Circle is a vibrant behavior setting during the lunch hour, with a great deal of interaction occurring both between and within participating user groups.

Perhaps the most common behavior in the pattern is people watching. On a typical day, a large majority of the Columbus Circle participants openly engage in this activity. The milieu of lunchtime Columbus Circle is particularly well suited for this behavior. With regard to the temporal aspects of the milieu, a summer weekday lunch hour is one of the times of peak pedestrian circulation in the CBD. This is obvious,

and it is a milieu characteristic which is, of course, not unique to Columbus Circle.

More interesting is the way in which the morphology of Columbus Circle serves the activity of people watching. The relationship of paths (invisible pedestrian corridors) and seating areas (benches and ledges) in Columbus Circle is such that most seats offer the individual a view, from a comfortable distance, of several lanes of movement. Furthermore, the seating areas are arranged so that users may discreetly view one another. One seating area, the southern quadrant of the fountain ledge, stands out among the others and can be considered a "stage" (an area that is a visual center of attraction and is visually connected to seating or viewing areas). Those who sit on the stage know that they are being watched, and they either choose to "perform" (become consciously involved with that visual interaction) or choose to ignore it. For those who wish to ignore it, the masking sound of the fountain facilitates insulation. Visual variety is evident: people can easily watch others within the context of paths, seating areas, and a stage.

A specialized and popular type of people-watching at Columbus Circle is girl-watching. The arrangement of seating areas and the stage serves this behavior remarkably well. The stage is not only the most visually accessible to other seating areas, but it is also the optimal sunning area. On a clear summer day, female office workers take to the stage, with their chins uptilted toward the sun and their legs outstretched in an unmistakable sunning pose. Of course, some are less dramatic and simply sit normally postured and chat with friends. Whether or not they perform on the stage, their presence encourages the presence of other groups in nearby viewing areas — specifically male white-collar workers and construction workers.

When interviewed, both these groups were explicit about their interest in the young ladies. Also, their location in the bench cluster in the southwest section of the Circle — an optimal position for viewing both the stage and paths — clearly demonstrates this interest.

The reaction of female office workers to construction workers is commonly negative: the earthy candor of the construction workers is not appreciated by the female office workers. In such proximity as just described, the construction workers' comments on the scene would perhaps be enough to convince the female office workers to move on. However, the sound of the fountain in the background is sufficient to remove the performers from their audience's verbal indiscretions.

Socializing is also a common activity in the Columbus Circle behavior setting: small groups engage in conversation, some individuals also moving freely among groups. The nature of the benches is such that six adults and their lunches can be accommodated comfortably on the same bench, and around the fountain ledge three adults can easily group together. Also, the visual and spatial proximity of seating areas makes it convenient to move from one area to another. The physical characteristics of Columbus Circle are highly compatible with gregarious socializing.

Related to people-watching and socializing is the activity of "hanging out" (waiting for spontaneous gatherings to occur). At least two features are required of a behavior setting so that it be appropriate for hanging out: first, it must serve as a popular gathering place; and, second, easy viewing of the space must be possible. As already discussed, Columbus Circle satisfies both these conditions.

Columbus Circle is, in short, "where the action is." Individuals gather to partake of the physical amenities and to interact socially with each other in a variety of ways. The milieu can be seen to encourage these pursuits.

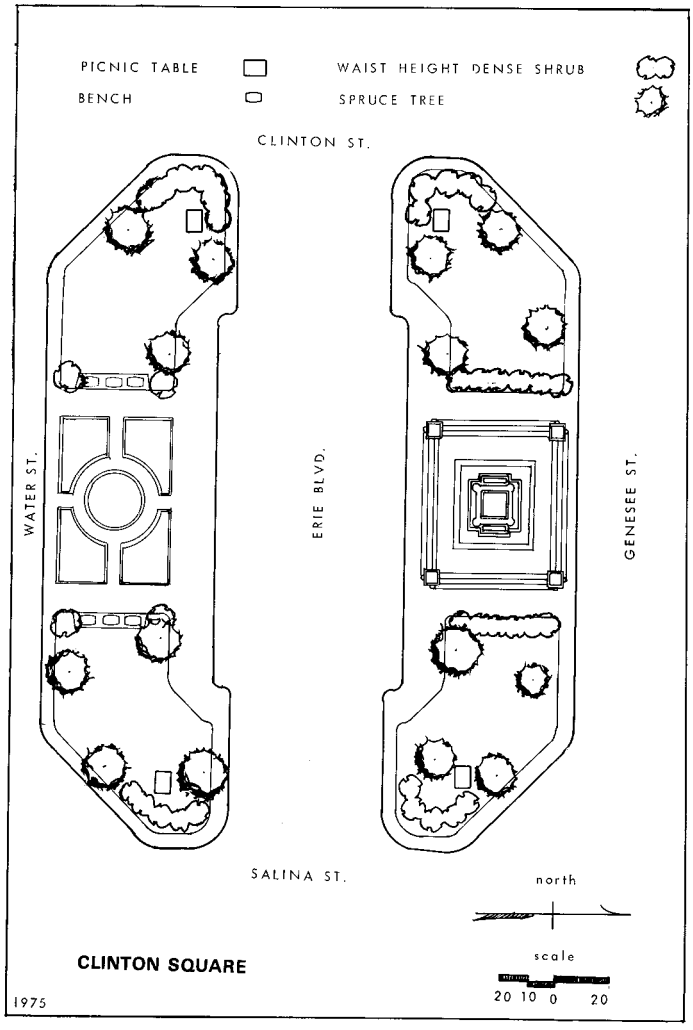
Clinton Square

Clinton Square is a spacious park situated in the northern part of the CBD at the intersection of two major four lane arteries (fig. 1 and 4). The space is bordered on three sides — north, east, and west — by busy streets and is bisected by a major boulevard. The park essentially comprises two large grassy, relatively peaceful islands protected by dense shrubs and spruce trees from enveloping currents of traffic.

Strictly speaking, Clinton Square is probably two behavior settings rather than one. The southern part, with its fountain, its relatively tranquil southern boundary, and its proximity to shopping, is easily the most popular. Our focus will be on this section.

Clinton Square is surrounded by municipal and commercial buildings; however, they are all separated from the Square by streets and parking lots. The buildings serve mainly as a backdrop to openness. Major employers are located nearby to the north and west of the Square. Because the principal lunchtime pedestrian flow is towards the main street on the park's eastern border, Clinton Square is a major pedestrian

Figure 4.—Clinton Square with its two parts, the fountain section to the south and the monument section to the north.



intersection at the noon hour. On the average, about 35 people use Clinton Square at lunchtime — slightly less than half the number using Columbus Circle.

Two user groups from the mainstay of the Clinton Square behavior setting: female office workers and construction workers. Interaction between the two groups plays little part in the character of the behavior setting.

Besides eating, only two types of behavior are common in the setting: socializing and "getting away" (any of a variety of solitary behaviors such as daydreaming, sleeping, and reading). The behavior setting is relatively quiet, and separate behaviors within the space are only tenuously integrated.

Socializing is the most commonly observed behavior in the setting. It is, however, a different variety than the type described in Columbus Circle. People come to Clinton Square in small groups, or they meet people there; they do not come to partake of a bustling social scene. Individuals are not seen visiting from group to group. Instead, private conversation and intimacy characterize the gatherings.

This type of low-key social scene can be better understood by examining the morphological aspects of Clinton Square's milieu. Intimate socializing is fostered by the compartmental structure and the limited seating of Clinton Square. The park is a series of seating areas separated by thick hedges, trees, and a fountain. The vegetation barriers provide both visual and acoustic insulation. Viewing lanes are generally not well developed, and it is impossible to scan the whole setting from any particular position.

Notice that despite the presence of female office workers, the highly compatible groups of male white-collar workers are not present. The barriers are so formidable that they restrict even the most aggressive girl-watchers — construction workers — to simple conversation among themselves. These characteristics not only make it difficult to feel a part of a large spontaneous social happening, but they also decrease the sense of protection characteristic of a highly integrated behavior setting. People can more easily feel vulnerable when separate from a large group. Also, the barriers make it difficult to assess possible threats present in the situation. These morphological restrictions on interaction and on situational legibility encourage many users to come to Clinton Square *with* their social companions rather than seek them in the space.

The other common behavior in the setting is "getting away". As just discussed, the morphology of Clinton Square provides ample privacy for any behavior from this set of solitary activities. Also, because of the morphology's effect on the nature of the socializing occurring in the behavior setting, solitary behavior blends well with the other common behavior. Getting away is not only physically possible but also socially consistent.

CONCLUSION

In comparing the lunchtime behavior settings at Columbus Circle and Clinton Square, we have seen the principle of behavior-milieu synomorphism in operation.

Each space has approximately the same contextual properties: easy access by all major user groups, a large number of potential participants, and proximity to restaurants and shops. Each space is a perceptual central place. Each space offers a similarly pleasant esthetic experience.

Yet, despite a host of similarities, two distinctly different behavior settings emerge from these spaces. We have seen that differences in behavior patterns can be directly linked to milieu differences. We have also specified some of the physical and social mechanisms by which this linkage occurs. Participants in these behavior settings respond to the physical pleasures of sun and attractive

sights and sounds. They also engage or disengage in a variety of social interactions such as talking to, watching, being watched by, and avoiding other people. We have seen how people, as physical *and* social entities, respond to different milieus to create different standing patterns of behavior.

It is often a tricky exercise to discuss the genuine behavioral significance of the environment free from deterministic overtones. Part of the problem is an inadequate vocabulary. In our discussion of Columbus Circle and Clinton Square, we have demonstrated that some of the concepts of ecological psychology can solve that problem. Within Barker's conceptual framework, we discussed behavior which was *compatible* with the milieu rather than behavior which was the *product* of the milieu. We discussed enduring *standing patterns of behavior* rather than bogging down in simple behavior. We noted that standing patterns of behavior and milieu were compatible in behavior settings *without* depriving individuals, even large numbers of individuals, of the freedom to behave in ways that are totally *incompatible* with the milieu. We feel that these concepts offer a profitable alternative to determinism — either physical or social — for those interested in environments and behavior.

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Perception of High-density Living in Hong Kong

by LAWRENCE H. TRAVERS, *assistant professor, State University of New York, College of Arts and Science, Oswego, N. Y.*

ABSTRACT.—Analysis of the Hong Kong experience of adaptation to urban living can provide insights into some of the problems that can be expected to occur in the rapidly expanding cities of the Third World. Population densities in Hong Kong are among the highest in the world, exceeding 400,000 persons per square mile in parts of Kowloon. Research based upon residence in a worker's dormitory and interviews with workers reveals a variety of adaptive strategies employed by people to cope with the stress of the crowded urban environment. An understanding of the individual's ability to adjust to the stress of high-density living must consider the meaning of density as a concept in the culture in addition to social and cultural norms.

DESPITE DECADES OF CONCERN about the possible effects of high living densities upon human behavior, we know very little about mankind's ability to adapt to crowded conditions. Fears persist that the presence of a behavioral sink among rat populations forced to live in very crowded quarters *(Calhoun 1962)* might have a correlate in human populations. Perhaps rather than simply observing human behavior in dense conditions, we might more profitably attempt to uncover the meaning of different crowded living situations for individuals in different societies. Analysis of the perceptions, as well as the behavior, of the inhabitants of cities like Hong Kong might help us to understand better why some areas of the world already overcrowded by most standards fail to exhibit a true behavioral sink.

Information about the concept of density was obtained by interviewing young Chinese worker-students in Hong Kong. For eight months in 1973 I lived in a worker's dormitory in Ngau Tau Kok, site of several large public-housing estates for low-income families and resettled squatters. Impressions were gained by living as much as possible the life of the residents of the area, through informal conversations with many of the residents, and through structured interviews with cooperative individuals.

ACTUAL POPULATION DENSITIES

Densities in Hong Kong are among the highest in the world. In 1971 the Mongkok area in Kowloon had a density of 154,677 persons per square kilometer (or 400,612 persons per square mile) which is almost five times the living density of Manhattan Island *(H. K. Census & Statistics Dept. 1971)*. In the area studied, the average family of five lives in a single room of about 120 square feet. Although in the newer housing estates each room has its own toilet and cooking space, in the older estates washing and toilet facilities are communal, and cooking is done on the exterior balcony which also serves as a corridor.

Though nearly half of the colony's population lives in such public housing, in 1971 there were still almost 30,000 squatters on the rooftops and hillsides in the urban area and 35,000 living in areas about the size of a bed-space. The congestion and crowded conditions in which nearly 4 million persons are living in less than 13 square miles of built-up land must truly be seen to be believed.

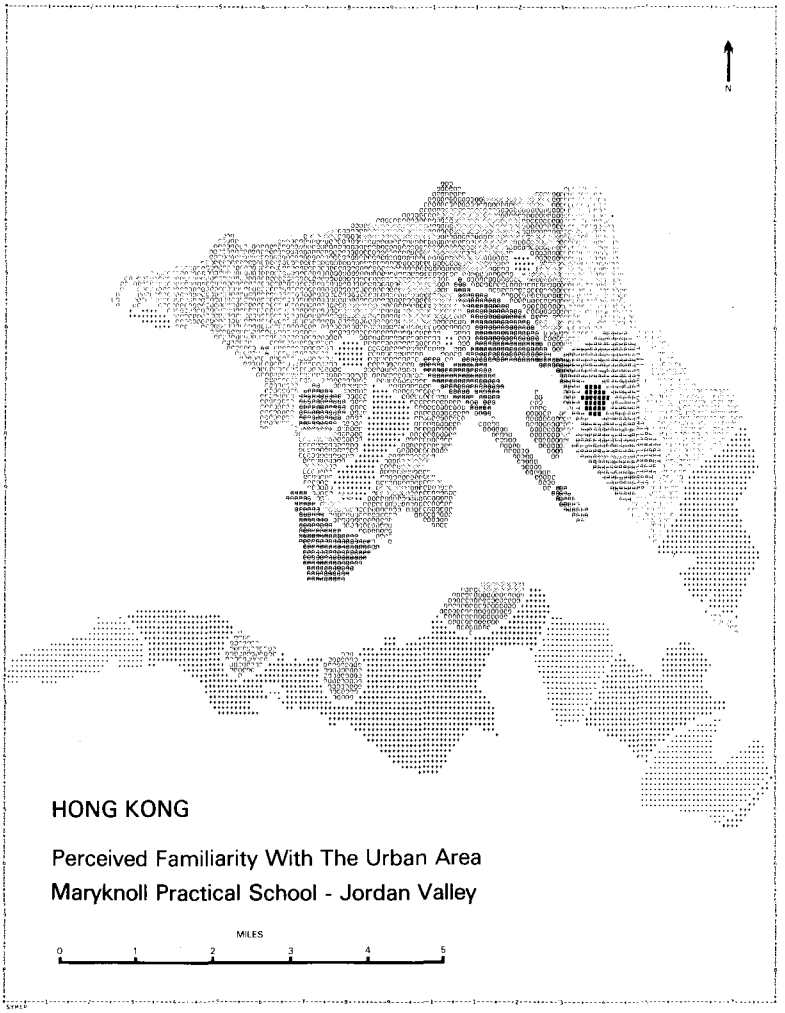
Crowded urban environments are, of

course, nothing new to the Chinese people. The Fengsheng neighborhood in Peking, considered to be fairly typical of other parts of that city, had a density of over 91,000 persons per square mile in 1972 *(Sidel 1974)*. Most of the buildings there were reported to be one- or two-story structures. Li Choh Ming *(1959)* has calculated that in 1957 the average housing space per capita in 175 Chinese cities was 3.5 square meters, varying from 4.9 in small cities to 2.2 in big cities. Of necessity Chinese both in China and in Hong Kong have learned to adapt to crowded living conditions.

PERCEPTION OF POPULATION DENSITY

To obtain comparable data about the Chinese perception of the urban area, 46 male adolescent workers attending evening classes at a secondary school in Kowloon were interviewed. Each was asked to indicate on a six-interval scale his familiarity with 58 urban districts (fig. 1). The students were then given a second questionnaire, which required them to estimate as best they could the average population density for the same 58 urban districts on a six-interval scale.

Figure 1.—Familiarity with the Hong Kong and Kowloon urban area; 46 workers attending a school marked by a dot have been averaged together. Darker shading indicates greater familiarity.



Estimations of the density of different parts of the urban area reflect knowledge of those areas obtained in several ways. Knowledge gained by travelling along the streets of the city, the "action space" concept of urban geography, can be termed experiential familiarity. Responses to both questionnaires clearly reflect this type of knowledge. A second type of familiarity, observational, is also apparent in the case of districts such as the Peak. Home of the Colony's most wealthy residents, the Peak can be seen from many parts of the city, and even if one has never been there it is not difficult to formulate ideas about the type of housing and number of persons living there. Observational familiarity plays an important role in forming the image of Hong Kong and Kowloon, twin cities separated by a deep harbor and fringed by hills.

Other parts of the urban area never visited nor observable from afar can still be known by what I have termed informational familiarity. Newspapers, television, and acquaintances are all sources of information about unfamiliar places in the city. Of course, most often what one knows of the city and of the population density of any particular part of it is an amalgam of these three types of familiarity. The individual is constantly bombarded with information; and while most is quickly forgotten, impressions of the urban environment remain.

Due to the fact that the format of the density questionnaire required an estimation of the population density, which might be unfamiliar to some individuals, it was necessary to weight each response to the density questionnaire by the individual's response to each item on the familiarity questionnaire. The students' estimations of the population density could then be averaged and mapped (fig. 2).

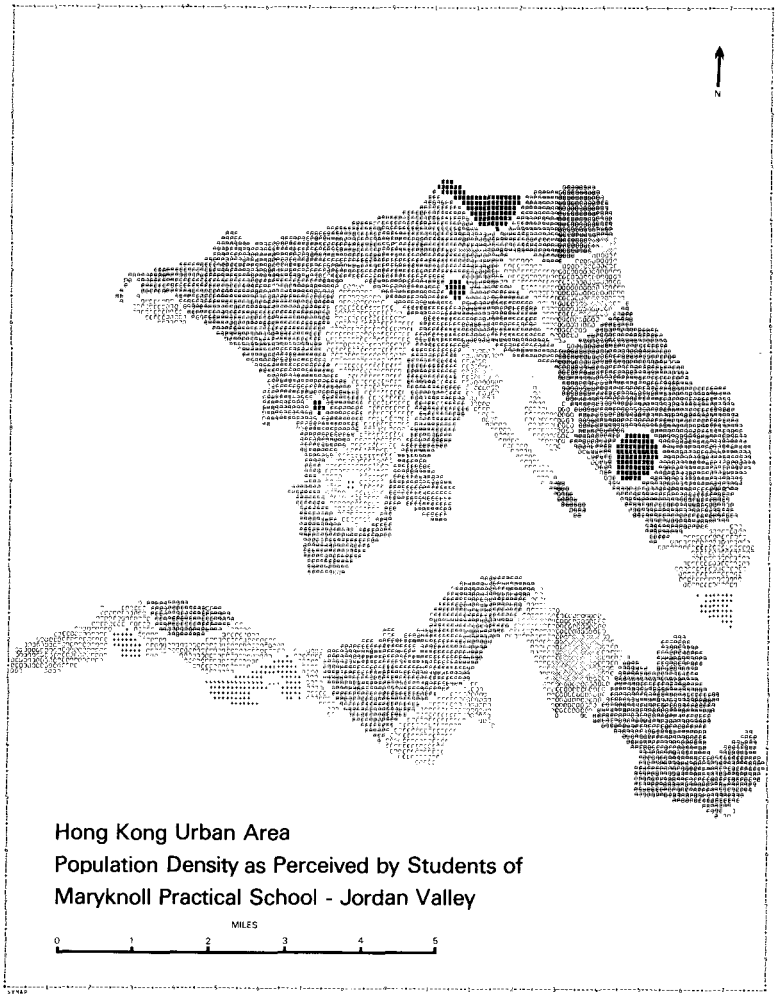
The averaged familiarity surface (fig. 1) indicates, as expected, that the district in which the school is located and where a majority of the students reside is most familiar. Major transportation corridors and business districts are well known; high-income residential areas, the urban fringe, and most of Hong Kong Island across the harbor are not very familiar.

The perceived population-density map (fig. 2) provides a generalized view of how these students view crowding and population density in their city. It indicates a high degree of uniformity as to which parts of the urban area are most crowded and which are least crowded. Surprisingly, the district in which most of the students live is not felt to be among the most crowded. This area, Ngau Tau Kok/Jordan Valley, had been selected for study because it was felt to be typical of the most densely populated residential areas in the city.

Assessment of the young worker-students' view of population density entailed comparing their perceptions with some measure of the actual population density for various parts of the city. This was accomplished by comparing the students' estimations with two very different measures of population density: net residential floor area per person and the number of persons per square kilometer for each urban district.

Net residential floor area per person is a measure of the degree of overcrowding in living quarters. It is calculated as one-half of the total floor area of a residential building, thus excluding kitchens, toilets, bathrooms, corridors, staircases, and landings. This information for 97 planning areas in the city was made available by the Crown Land & Survey Office of the Hong Kong Government. Aggregated to 58 districts and standardized, these data could then be compared with the standardized scores of the estimated population density, using Spearman's rank correlation. There is no similarity between the perceived and actual density measures for districts in Kowloon ($r_s = -0.06$) and

Figure 2.—The perception of urban area population density. Darker shading indicates more densely populated areas.



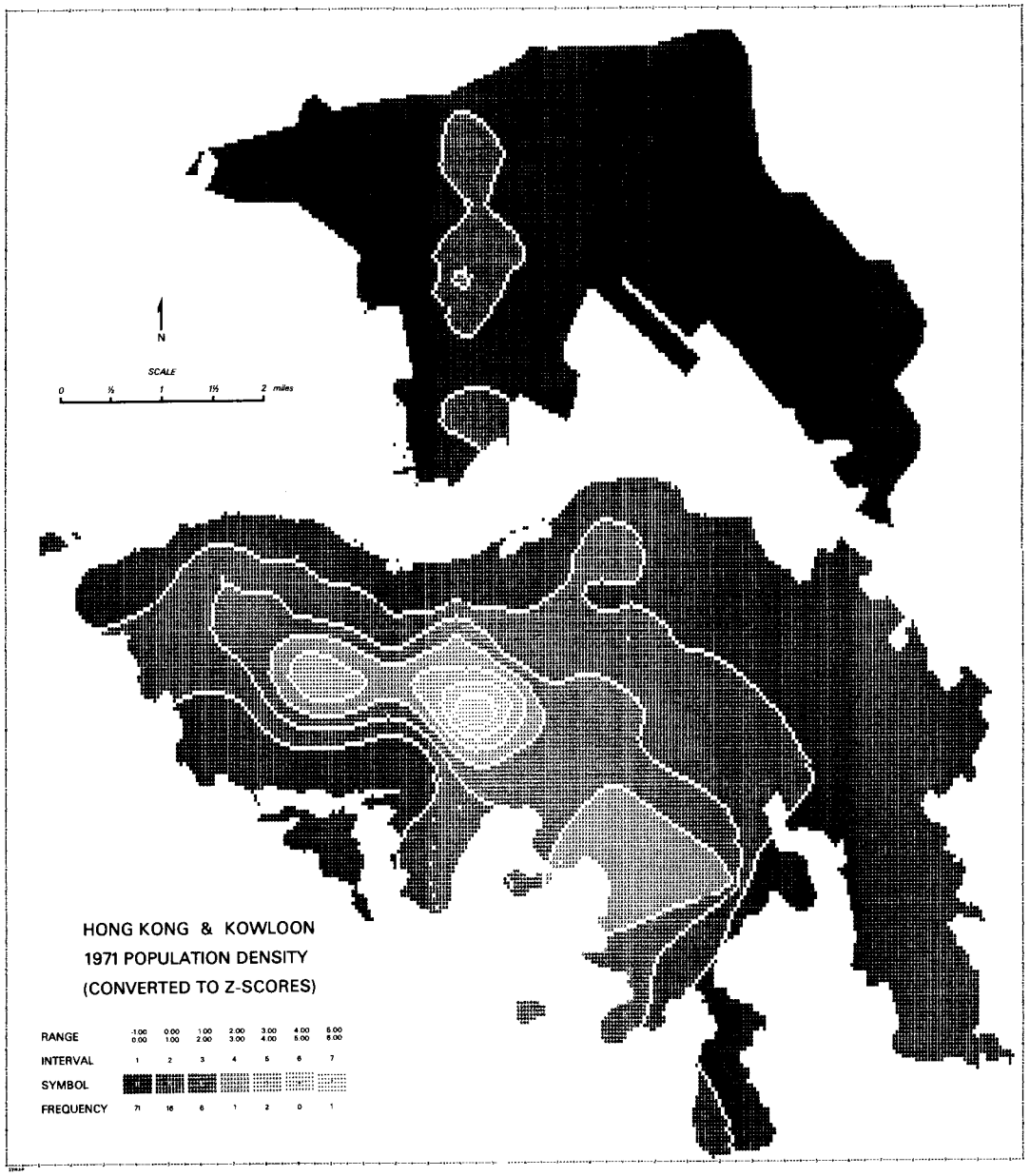
only minor similarity for districts located on Hong Kong Island ($r_s = 0.52$).

The population density perceived by worker-students is much closer to the other measure of density, the number of persons per square kilometer. The number of persons living in each city block was available from the 1971 Hong Kong Census of Population; the area of each of the 58 districts was measured, using a polar planimeter. Comparison of the perceived density measure with the number of persons per square kilometer shows a high degree of correlation. The similarity is highest for districts on Hong Kong Island ($r_s = 0.88$) and only slightly lower for districts in Kowloon ($r_s = 0.83$).

DISCUSSION

The fact that worker-students' perceptions of the urban population density closely approximates the actual number of persons per square kilometer reveals

Figure 3.—Actual population density of the urban area computed as the ratio of net residential floor area per person.



something about their concept of density. While it is highly unlikely that these individuals had in mind any idea as complex as "number of persons per square kilometer," they probably were interpreting the concept of dense or crowded conditions to mean the everyday sidewalk population of each urban district. An area of the city is considered densely populated in terms of the number of people one should expect to observe and rub shoulders with when walking the streets of the city.

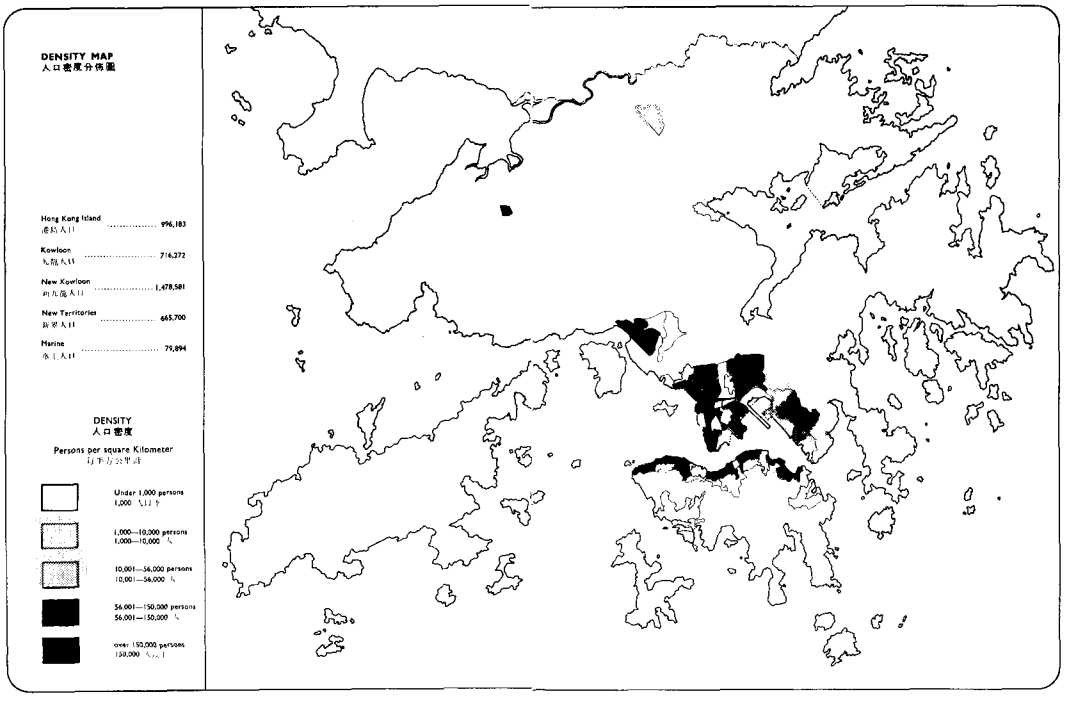
Despite the fact that most of the urban area, except for that inhabited by the very rich, has a net residential floor area of 25 square feet per person, this uniformity of living density was not

perceived by the respondents. Perhaps this type of density is less obvious, being hidden behind the facades of countless buildings. More likely, it indicates that the term for dense, crowded conditions, *chàuhmaht* in Cantonese, is not usually identified with lack of space in one's living quarters. Indeed, as Goodstadt *(1969)* and Hopkins *(1971)* have shown, the quality and amount of dwelling space are not a major concern of most Hong Kong Chinese. Only the very wealthy in Hong Kong can improve their living accommodations; all others must be content with a place in which to cook, sleep, and store possessions.

Despite such high densities, the Chinese in Hong Kong appear to have made a successful adjustment to the present situation. Several studies have revealed that the Chinese family in Hong Kong has learned well how to cope with the environmental stress of crowding. Schmitt *(1963)* found little relationship between density and crime rates or morbidity. Mitchell *(1971)* found a high tolerance for crowded living conditions among Chinese so long as only one household occupied the dwelling unit. On the other hand, Anderson *(1972)* found that even when three families were forced by economic circumstances to live together, the situation was made tolerable by the adoption of behavioral norms that were rigidly enforced by all. These studies reinforce the finding of Kaye *(1960)*, who studied the Chinese inhabitants of an old lane in Singapore. She found a highly structured code of behavior for both children and adults.

In Ngau Tau Kok, most families are highly tolerant of their neighbor's activities. The clacking of plastic tiles in playing the game of *Mahjong* at 3 a.m. and children playing in the corridors of the buildings is no cause for one to become angry. Arguments, even when of

Figure 4.—Actual population density map of Hong Kong computed as the number of persons per square kilometer.



a very personal nature, are carried on in public, and neighbors often become involved.

Individuals spend as much time as possible outside the home, and many young adults return only to eat and sleep. Housewives shop in street markets at least twice daily, carrying their infants on their backs; young unmarried workers enroll in evening courses at schools; husbands returning home after working 10 hours escape into the fantasy world of television.

Some methods of coping with the crowded urban environment, on the other hand, show evidence of what might be called social pathologies. Despite the relatively low incidence of serious crime, many people live in a world of fear where every young male is believed to be a potential robber or mugger. The doors and windows of every home are barred with special steel gates; the city imprisons itself each night. Drugs and gambling are serious problems throughout much of the urban area. Little concern is shown for anyone in need who is not a relative or close friend. However, this social anomaly, often described by social workers and government officials, is probably not as much a result of the crowded living conditions as of the continued inability of most Chinese to identify with a foreign colonial government. Alienated from his homeland in China and uncertain of the future political status of the colony, many individuals have simply ceased caring about anyone outside the family.

CONCLUSION

The ability of Chinese, both young and old, to cope with the crowded living conditions that exist in most parts of Hong Kong is closely tied into the social fabric of Chinese society. Most people have made a successful adjustment to living densities that most Westerners would find intolerable. The ability of individuals and families in other societies to adjust to such high living densities in the rapidly growing cities of the Third World is difficult to predict because few places have yet experienced the densities of urban Hong Kong and Kowloon. Assessment of their ability to adjust must take into consideration the individuals' psychological perceptions of density in addition to the social and cultural norms of the society.

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Acknowledgments. Field research was supported by a dissertation grant from the Technology and Development Institute of the East West Center in Honolulu, Hawaii. The author thanks the Maryknoll Fathers for permission to conduct classroom interviews and the Hong Kong Government for providing access to unpublished data.

Visual Land-use Compatibility and Scenic-resource Quality

by WILLIAM G. HENDRIX, *research associate, Department of Landscape Architecture and Regional Planning, University of Massachusetts, Amherst.* *This study was supported primarily by the Massachusetts Agriculture Experiment Station, University of Massachusetts (Paper 1072). Additional support was received from the USDI Office of Water Resource Research and the USDA Forest Service, Northeastern Forest Experiment Station, through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Studies.*

ABSTRACT.—The effect that land-use relationships have upon perceived quality of the visual landscape is discussed, and a case is made for expansion of fit-misfit theory into what has been called visual land-use compatibility. An assessment methodology that was designed to test people's perceptions of land-use relationships is presented and the results are discussed.

TRADITIONALLY, IN THE ANALYSIS of visual landscape quality, the parameters used most often are landscape diversity, landscape contrast, and landscape complexity *(Fabos 1973, Green 1972)*. In most of the assessment techniques, only the quantitative aspects of land-use adjacencies are considered. They consider only the length of the adjacency and degree of contrast between land uses. There is much evidence that people do indeed respond in a positive way to complexity and contrast *(Berlyne 1963, Day 1967, Munsinger and Kessen 1964, Lechart and Bakam 1965)*. Nonetheless, we are faced with the very real possibility that many of the land uses that contribute to contrast or complexity are themselves undesirable or are incompatible with other adjacent uses. This raises the need for a technique for qualitative assessment of land use relationships.

A review of historically related planning literature reveals that man has always been concerned with relationships between land uses in the development of communities. Early cities, for instance, were placed along or near bodies of water that provided the inhabitants with an adequate supply of water, transportation, waste disposal, and security from invading forces. This same need for security had a great influence on other development patterns. Forest land was not maintained immediately adjacent to communities because it provided concealment for attacking forces. Agricultural land on the outskirts of the cities not only provided necessary farm products, but also allowed ready observation of approaching visitors *(Mumford 1961)*. A less justified but nonetheless very real fear of the forest as a wilderness home of wild beasts and monsters further influenced the forest-town relationship *(Nash 1967)*. When the first Europeans arrived in America, the wild and natural environment they found reinforced these perceptions. Protection from the real and imagined enemies that lurked in the vast wilderness and development of farmlands led in part to the removal of much of the forest land throughout New England.

Late in the nineteenth century in the United States as well as Europe, perceptions of land-use relationships had begun to change. The romantic landscape movement in England and the subsequent park movement in the United States were the first evidences of these perceptual changes. In England,

these movements were led by William Kent, Capability Brown, and Humphrey Repton. American leaders included Andrew Jackson Downing, Frederick Law Olmstead, and John Muir. By this time, people were beginning to see the value of natural elements in the landscape.

Early interest in land-use relationships was reflected in nuisance law. "While many land use incompatibilities are a product of physical damage flowing from close proximity, in many cases the conflict is predicted solely on matters of taste and preference rather than an observable physical effect" *(Mandelker 1970)*. By late in the nineteenth century, the separation of incompatible land uses had begun to take the form of present-day zoning. In the 1880s or 90s, Chinese laundry establishments in San Francisco were prohibited or restricted in certain parts of the city. When contested, the decisions were upheld in the courts as being valid use of the police power. Early in the twentieth century, zoning ordinances had become the common form of land-use regulation in the United States. The ordinance enacted in New York City in 1916 was the first of these *(Toll 1969)*. Since that time, zoning has become the most widely used method of land-use control and clearly represents a concern for the separation of what are perceived to be incompatible uses.

In developing methodologies for assessing metropolitan landscapes, land-use compatibility may be an important parameter. Although recent research has shown that land-use compatibility plays an insignificant role in influencing perception of visual quality at the natural end of the landscape continuum, *(Anderson et. al. 1976)*, it may play a major role at the urban end. This is explained by the fact that nearly all elements in a natural landscape are found to be compatible with one another, while the metropolitan landscape is made up of a variety of elements that are incompatible. Those rare elements found in the natural landscape that are incompatible with their surroundings can be treated as misfits. The occurance of incompatible uses in the metropolitan landscape is so frequent that they cannot really be termed misfit. Thus the application of land-use compatibility concepts to the metropolitan landscape can be thought of as an extension of misfit theory.

The research reported here was conducted to develop a methodology for assessing visual land-use compatibility in the metropolitan landscape. This research represents only a small part of a larger ongoing project at the University of Massachusetts, called the Metropolitan Landscape Planning Project (METLAND).

METHODS

This research had three primary objectives. The first was to identify a technique that could be used to determine compatibility values for possible land-use adjacencies in the metropolitan landscape. The second was to translate these values into a procedure for assigning actual scores to the landscape. The third was to apply the entire procedure to a study area in the Boston metropolitan area.

Although there is considerable literature about land-use compatibility, no clear technique for determining values exists. To resolve this problem, a testing procedure was designed. It was hypothesized that the relationship between two adjacent land uses may be a function of the effect that each land use has upon the other. That is, the relationship between land uses A and B would be a function of the effect that A has on B and the effect that B has on A. Furthermore, the effect of A on B might be significantly different from the effect of B on A. For example, in consideration of a forest/residential adjacency, the effect of the forest upon the residential areas might be positive while

the effect of the residential area upon the forest might be negative. Thus the combination of these two effects could be considered a parameter of visual land-use compatibility.

The METLAND Study has used a land-use classification system generated from aerial photography by the Department of Forestry at the University of Massachusetts *(MacConnell 1972)*. Since its initial development, the system has been modified and expanded, and with the addition of several urban uses it now includes 126 distinct land types. This same classification system was used as a basis for the land-use compatibility component of the study. A few simple calculations show that this system generates an enormous number of land-use adjacencies. Using the formula

$$A = \frac{n^2 - n}{2}$$

where A is the total number of possible adjacencies, and n is the number of land uses, we find that there are 7,875 possible adjacencies. Obviously it is impossible to consider the visual compatibility of such a large number of adjacencies. Furthermore, the distinctions that can be made among many of these 126 land uses are relatively insignificant, especially with respect to visual characteristics. For instance, the difference between two forest types — H3A and H4A — is only in the heights of the trees, 30 feet and 40 feet respectively. Both are relatively mature forests, and the visual distinction is slight.

The first task was to find a technique for aggregating these 126 land uses into a smaller number of common types. It seemed that the maximum number of adjacencies that could be considered was approximately 100. This meant that the 126 types would need to be collapsed into 15 or fewer general classes (15 types would produce 110 adjacencies).

To accomplish this aggregation, a group of designers, planners, and resource managers were asked to sort 126 cards, each describing a land use, into 9 categories ranging from most man-made to most natural. Examination of the data received from this survey identified 10 distinct groups consisting of land uses with similar visual characteristics. For example, all of the land-use types that fell into the wetland category were obviously associated with water, consisted primarily of low vegetation, and lacked man-made structures; while those types that fell into the industry category were represented by large densely-built structures and a lack of vegetation or open land. An eleventh category, open water, was added because of its importance in influencing perceptions. These 11 general land-use groups, each representing a number of more specific land-use types having similar characteristics, were chosen for further study.

In any research of this nature, it is desirable to obtain as large a sample as possible. Generally the larger the sample, the more valid will be the results. However, other constraints such as limited personnel, finances, and time place restrictions upon the number of responses that can be obtained. For this study, it appeared that 50 responses was the maximum number that could be gathered in the time available and was an adequate number to achieve the desired results. To test a wide cross-section of the population, the 50 respondents were selected from 5 subgroups: designers (architects, landscape architects, and interior designers), planners (regional planners and community planers), realtors, conservationists, and nonprofessionals. It should be noted that nonprofessionals as used here is meant to include people who are not familiar with land-use related issues. Ten individuals from each of these 5 groups provided the sample of 50 respondents.

To elicit responses from participants, some sort of environmental stimulus is needed. This stimulus can be as simple as a written description, or as complex

(to administer) as an actual on-site inspection. Again, time and money constraints greatly influenced our choice of a procedure. For this study black-and-white photographic prints of the eleven general land-use types were selected. Recognizing the difficulty in locating typical examples of each land use, we decided to produce 3 sets of photographs of the 11 general types.

An attempt was also made to control as many variables as possible in the photographs. The following criteria were used in selecting and photographing examples of land uses:

- All photographs were taken on sunny cloudless days in late spring between the hours of 10:00 a.m. and 2:00 p.m.
- Topographic relief was held constant in all photographs. Only sites with slightly rolling or flat topography were photographed.
- The amount of foreground was kept constant in all the photographs. This was accomplished by keeping the foreground line at the same position in the view finder of the camera for each photograph.
- The horizon line was kept constant in all the photographs.
- All photographs were taken from a normal viewer position.
- Each photograph was to represent only one land use.

To maintain consistency of procedure, all of the 50 surveys were administered by the author. Each participant in each subgroup was randomly assigned to one of the three sets of photographs so that 3 persons from each group responded to set A, 4 to set B, and 3 to set C. Each participant was shown all 11 photographs so that he or she would be familiar with the general land-use types. After this, one of the photographs, randomly selected, was placed on the participant's left. The remaining 10 photographs were then presented in a predetermined random order on the right. In all cases the participant was asked to respond to the following question:

> If the two land uses represented by the photographs you are observing were adjacent to one another, how would the land use on the right affect the visual quality of the land use on the left?

After all 10 photographs had appeared on the right, a different photograph was placed on the left, and the procedure was repeated until all 11 photographs had appeared on the left and had been compared with the other 10, making a total of 110 observations. The participants were asked to record their responses on the following scale:

$$-3 \quad -2 \quad -1 \quad 0 \quad +1 \quad +2 \quad +3$$

If the land use represented by the photograph on the right had no effect upon the visual quality of the land use represented by the photograph on the left, the participant was asked to record his response in the space marked 0. If the one on the right enhanced the one on the left, the response would be recorded in the appropriate space on the positive side of the scale. If the one on the right detracted from the one on the left, the response would be recorded on the negative side of the scale.

FINDINGS

The results of the survey are presented here in two ways, first in relation to the consistency of the responses between the five subgroups and secondly, in relation to the actual compatibility values themselves. It was assumed at the outset that the extent of agreement among participants would not be the same for all of the adjacencies. To test this assumption, an analysis of variance was conducted to examine the variance between the 5 groups for each of the 110 observations (fig. 1). It should be noted that each relationship in the matrix, representing a possible adjacency, is derived from the combination of two observations. If there were no

Figure 1.—Extent of agreement matrix.

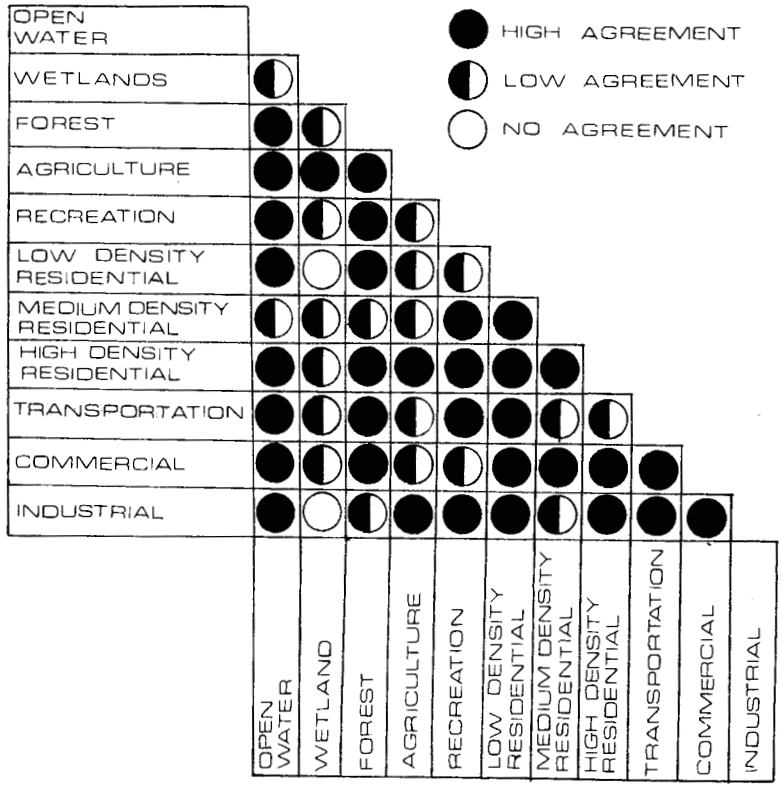
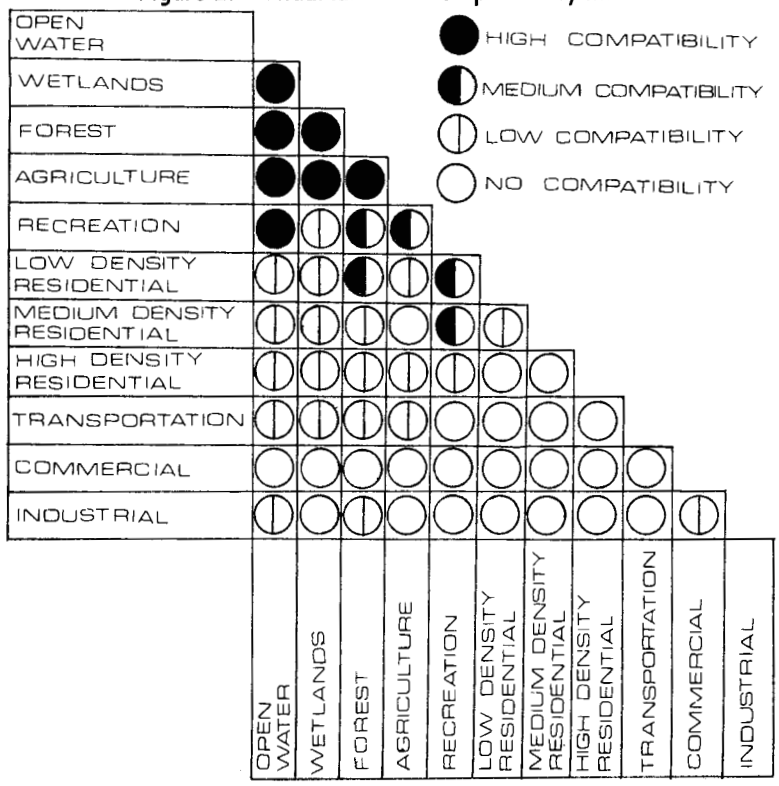


Figure 2.—Visual land-use compatability matrix.



disagreement between groups for either of the two observations, the agreement on that relationship was considered to be high; if there were disagreement between groups on one of the observations, the agreement on that relationship was considered to be low; and if there were disagreement between groups on both of the observations, there was considered to be no agreement on that relationship. There was considered to be disagreement on an observation when the scores from the 5 groups were found to be different at the 95-percent confidence level.

The actual compatibility values are recorded in figure 2. Again it should be noted that each of these values represents the scores obtained for two observations. The mean scores of all 50 participants for each of the 2 observations were added to derive the single value for each adjacency. The values were found to range from a low of −1.98 to a high of 4.78, which when normalized vary between 0 and 6.76. These values were then distributed into the four classes of visual land-use compatibility listed below:

High compatibility	4.51 - 6.76
Medium compatibility	3.01 - 4.50
Low compatibility	1.51 - 3.00
No compatibility	0 - 1.50

These visual land-use compatibility ratings (fig. 2) were applied to a preexisting assessment technique. A further discussion of that technique can be found in Fabos *(1973)* or Hendrix *(1973)*.

CONCLUSIONS

Several conclusions can be drawn from this study. It seems reasonable to expand the concept of *misfit* into a broader concept that expresses the relationships that exist between adjacent land uses. That is, people respond to all manner of relationships, not just to those that represent misfits.

This research was not designed to examine the multivariate aspects of land-use compatibility. The survey was made in such a way as to elicit responses about the visual aspect of compatibility only. In spite of this, several participants expressed concern for other aspects while being interviewed. Housewives, for instance, commented about the safety aspects of a housing and transportation adjacency. Similarly, many participants seemed to be concerned about other than visual aspects when confronted with an adjacency involving wetlands. While the developers expressed economic interests, the conservationists seemed to be concerned with pollution and loss of wildlife habitat. This may in part explain why there is so little agreement about wetlands adjacencies between groups (fig. 1). It could be concluded that more research, perhaps by environmental psychologists, is needed to resolve this problem.

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A Computerized Model for Integrating the Physical Environmental Factors into Metropolitan Landscape Planning

by JULIUS GY FABOS *and* KIMBALL H. FERRIS, *respectively professor in landscape planning and research associate, University of Massachusetts, Amherst, Mass.* *This study has been supported primarily by the University of Massachusetts Agricultural Experiment Station (Paper No. 1059). Additional support has been received from the U. S. Department of Interior Office of Water Resources Research and the USDA Forest Service, North-Eastern Forest Experiment Station, through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Forestry Studies.*

ABSTRACT.—This paper justifies and illustrates (in simplified form) a landscape planning approach to the environmental management of the metropolitan landscape. The model utilizes a computerized assessment and mapping system, which exhibits a recent advancement in computer technology that allows for greater accuracy and the weighting of different values when mapping at the regional scale. It assesses resource, hazardous, and developmentally suitable areas in order to determine the consequences of development in these areas, and to channel development to the most environmentally appropriate of these areas.

PHYSICAL ASSESSMENT and planning models have traditionally been developed to deal with four aspects of landscape resources. These are quality, quantity, location, and distribution. When these four aspects of the physical environmental resources are known, decision-makers are able to make better trade-off decisions.

Landscape-planning procedures during the 1960s provided decision-makers with relatively useful composite maps showing where higher-quality landscape resource occurred in large quantities. These early planning processes, however, were not able to distinguish the values of the various resources. The computerized model described here represents a parametric approach to landscape planning that has the capability of weighting the values derived from perceived environmental quality. The model was designed primarily for those landscapes that are experiencing major development pressures at this time.

This paper is a summary of the most recent assessment model developed by a University of Massachusetts research team named METLAND. Its objective is to present an environmental/landscape assessment procedure that can be used to estimate: those special resource values thought to be essential for metropolitan population; potential natural and man-made hazards resulting from poor land-use decisions; an assessment of environmental opportunities for development termed developmental suit-

ability and the production of an ecologically acceptable use type, development, density, and distribution plan of the Boston metropolitan region.

Since the second world war, metropolitanization has been one of the major contributors to environmental degradation. In contrast to the highly concentrated cities of the early industrial nations, which comprised only a few square miles, this new metropolitan growth extends its effects for several thousand square miles. Metropolitan regions are often interconnected to form megalopolitan regions such as the urbanized Northeastern Seaboard of the United States *(Gottman 1961)*. Since the 1950s this region has spread over more than 35,000 square miles of the landscape.

This mammoth metropolitanization has precipitated many undesirable side effects. It has eliminated or impaired untold acres of valuable natural resources such as water, upon which all life depends. Much of the development has occurred in areas subject to hazards such as flooding, noise, or air pollution. Developers selecting sites for development often did so in blatant disregrad of existing site characteristics. As a result, wetlands have been filled, unnecessary erosion problems have occurred, and developments have been located in climatically disadvantageous areas such as slopes facing into prevailing winter winds. Moreover, esthetic opportunities of developing areas have largely been ignored. Finally, the natural energy flow of existing ecological systems has been seriously taxed because of an almost total lack of concern for basic ecological principles in the planning of metropolitan landscapes *(Odum 1969)*. In responding to these problems, a subfield of planning or regional design has emerged under the name of *landscape planning*.

The METLAND research group noted above, comprised of over 16 researchers, is concerned with these landscape-planning problems. The group has been developing and refining landscape-assessment procedures since 1971 *(Fabos 1973)*. These procedures are aimed at providing a meaningful and useful tool to aid all regions exposed to metropolitan growth pressures. More specifically, however, the study focuses on the problems of the Boston Metropolitan region, which has relentlessly expanded to engulf over 2,500 square miles, or almost half of the State of Massachusetts *(Ferris and Fabos 1974)*.

The model, although still in the process of development, is sufficiently advanced to show the step-by-step procedure used in its four components. The specific purpose of this paper is to put into perspective and illustrate in simplified form the significance of synthesizing the information generated by these components. Examples of some of the specific procedures for gathering assessment information may be seen in other METLAND papers included in these proceedings *(Caswell and Jakus, Fahrer and Peters, Hendrix,* and *Joyner and others)*.

An additional specific aim is to show the capabilities of the second generation computer graphic tools. These are used to integrate the values of the many landscape variables and the four components listed above and to study the cause-effect relationships of development and impact prior to implementation. In addition, these tools demonstrate how the existing research results of several disciplines can be used as input in an environmental or landscape-planning model.

IMPETUS FOR THE METLAND STUDY

The environmental or landscape planning considerations discussed here are certainly not new. Charles Eliot II, the founder of the first metropolitan system of parks, for example, frequently expressed great concern for the public values of wetlands, water and scenic values, during the late 19th century *(Newton 1971)*. The famous landscape

planner, Benton MacKaye, voiced similar concerns during the 1920s *(MacKaye 1962)*. Nevertheless, systematic landscape resource, hazard, and suitability assessment was not practiced until the 1950s and 1960s.

One of the most outstanding members of this generation of landscape planners is Ian McHarg. In his book, *Design with Nature,* he proposed a generalized landscape approach for assessing large landscape such as metropolitan regions *(McHarg 1969)*.

Simultaneously, by the late 1960s the first generation of computer graphic techniques was being widely used for the data manipulation of landscape variables *(IRIS 1972)*. This technique was applied manually by overlaying a grid on the various resource and data maps of a given region. For each grid cell several types of resource data were processed into the computer. Once in this form, the data could be manipulated to provide print-outs of assessment maps. This technique is still valuable for some generalized regional assessment such as air pollution. It is less useful, however, for manipulating more detailed data such as soil, vegetation, or land-use types.

Remote-sensing capabilities and other land-use survey techniques also began providing landscape planners with relatively accurate data during this period. Although the data were quite accurate, the smallest land-use map units (grid cells) which could be realistically prepared by the computer use from airphotos were about one hectare *(MacConnell 1956)*.

Soils, surficial geologic, and other pertinent environmental data were also available at a high degree of accuracy, but they too could be practically manipulated only at the 1-hectare size. While all these pieces of information are meaningful for landscape resource, hazard, and suitability assessment, the first generation 1-hectare grid cell is too gross to assess them accurately. If grid cells smaller than 1-hectare were used in this process, the data processing would be overly costly and extremely tedious.

For this reason the METLAND team searched for computer software more responsive to its landscape-planning needs. Among all the computer graphic techniques surveyed in 1973, the Computer Mapping for Land Use Planning (COMLUP) system *(Allen 1973)* seemed most appropriate for our study.

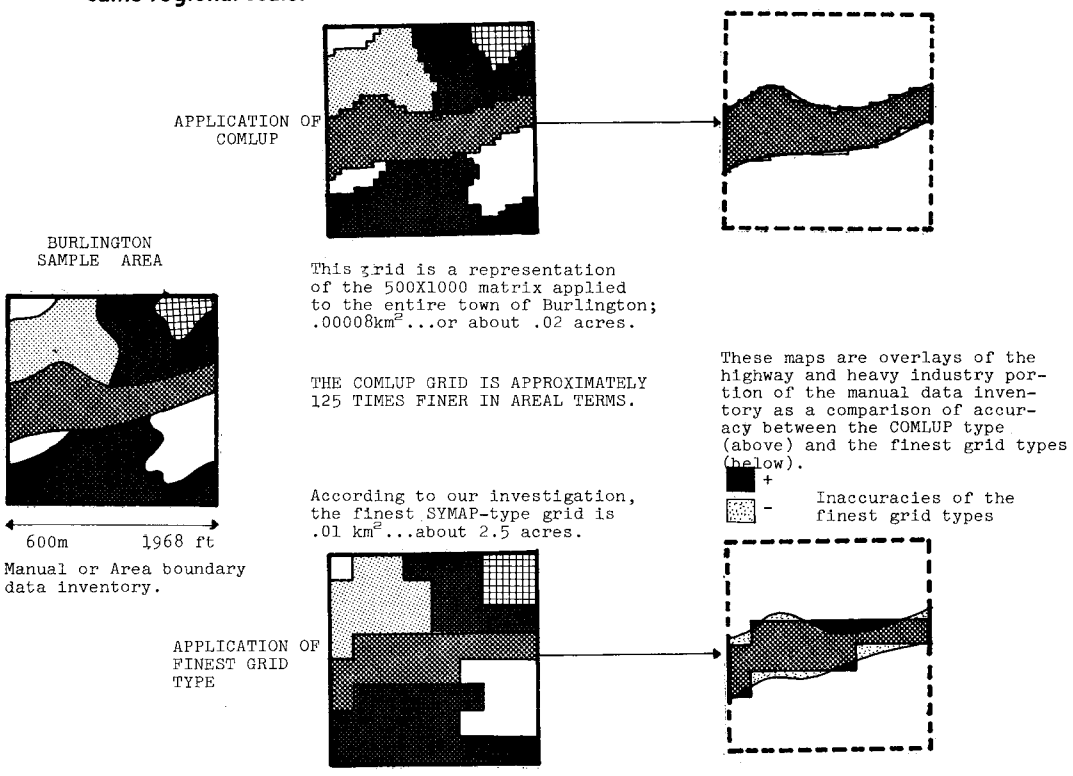
The advantage of this computer graphic technique is that any shape and size of polygon can be directly input and stored in the computer, by image digitizer, without subdividing the polygon into grid cells. For data manipulation, the digitized area still must be subdivided into cells, but this is now done in a second step by the computer automatically, instead of as a first step and manually. In addition a much finer cell granularity with a grid matrix of 500 X 1,000 cells is now possible.

Figure 1 shows the advantage in accuracy of COMLUP (an example of this second generation) over the first-generation computer grid technique when applied at the regional scale. With this new capability the more accurate data being produced may be better used by landscape planners.

While landscape planners are utilizing this second generation of technology, computer programmers are working on a third generation, which is being designed to overlay polygon areas directly without the interim step of converting it back to grid cells for manipulation. The Canada Geographic Information System Group of the Canadian Federal Government and the U.S. research firm Raytheon are among those in the process of developing this more advanced third generation of computer graphic software systems.

The remainder of this paper focuses on the METLAND environmental/landscape-palnning model, with special emphasis on the assessment procedure, including some sample results. The model is presented by first examining its

Figure 1.—The relative accuracy of the first generation (grid type) and second generation (modified grid type) computer mapping systems when applied at the same regional scale.



overall framework. Then the synthesis of the special resources component of the assessment phase is presented, and the significance of the results is discussed. A comprehensive report is now being prepared on the entire assessment procedure.

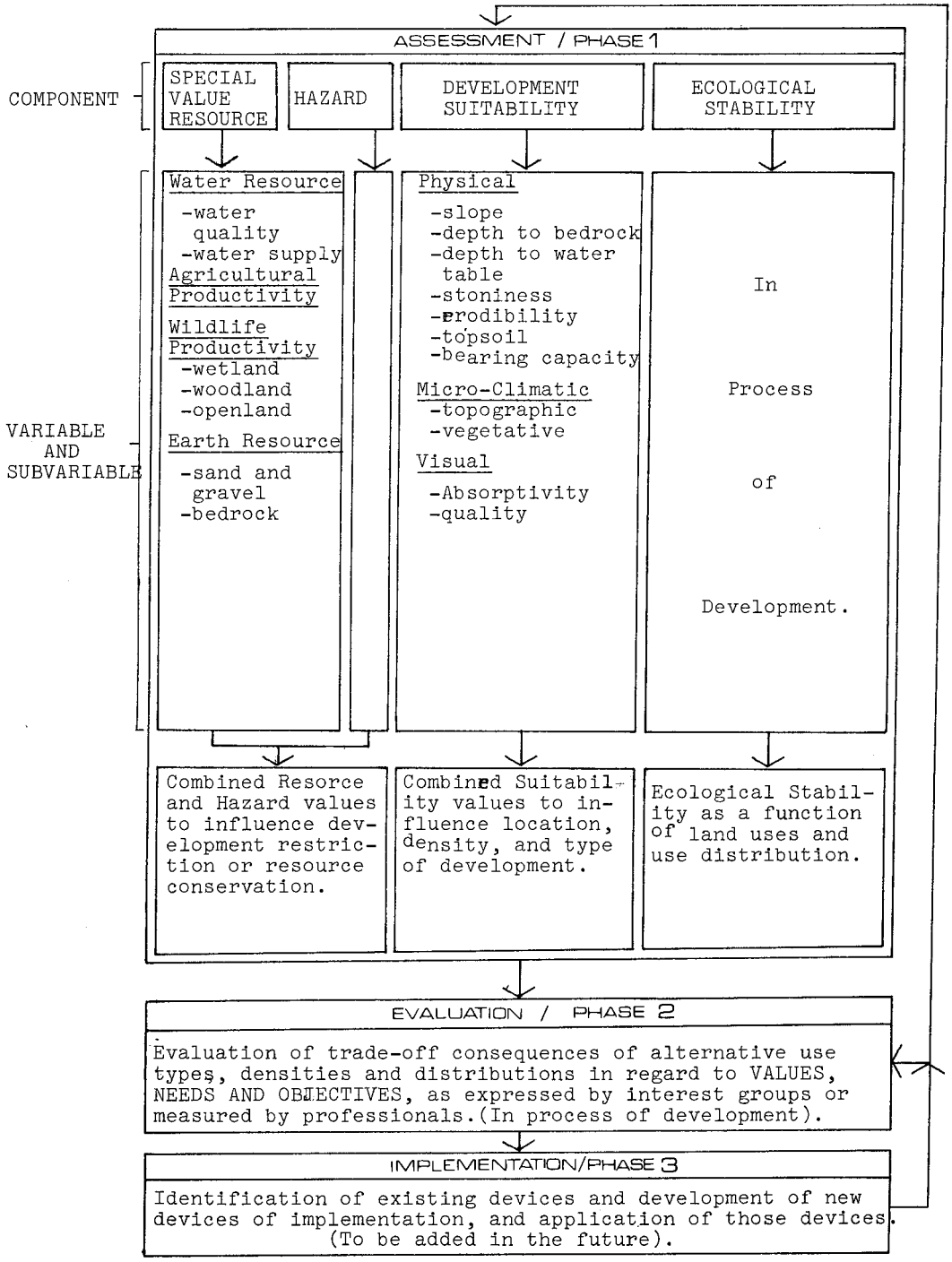
FRAMEWORK OF THE METLAND (ENVIRONMENTAL/LANDSCAPE) PLANNING MODEL

To deal adequately with environmental issues of the metropolitanized landscape, the METLAND team has proposed a three-phase planning model including assessment, evaluation, and implementation phases (fig. 2). At this point the assessment phase is close to completion, and some work has begun on the evaluation phase; the implementation phase is planned for later development.

The assessment phase consists of a selection of variables analyzing the intrinsic value of landscape resources which may provide societal benefits. This phase also analyzes natural or man-effected hazards that may cause harm to people or property. These several resource and hazard analyses are mapped and organized into four groups, called components. While each individual variable has a specific value, this grouping helps to identify complementary relationships and to provide combined values, which are useful in making decisions. The four components of the assessment phase are: special value resources, hazards, development suitability, and ecological stability.

The special value resource component (fig. 2) includes those natural renewable, nonrenewable, and esthetic resources whose maintenance is essential

Figure 2.—The structural framework of the METLAND (Environmental/Landscape) Planning Model.



for metropolitan populations. Development of these resource areas would eliminate or greatly impair their value. Though these resources are ubiquitous, their quality and quantity range from the insignificent to the critical. The assessment of this component is based on the premise that if a portion of a landscape possesses high quality and quantity of one or more of these resources, those areas should receive special consideration or even protection from development. If immediate need for the resources is not apparent, they should be protected or conserved much as capital resources are saved in a bank until they are needed.

The hazard component (fig. 2) includes air and noise pollution, both of which are direct human byproducts, and flood hazard which, although it is a natural phenomenon, is both aggravated and intensified by human activity. Flooding becomes harmful only when development is in nature's way.

The assessment of these three hazard component variables provides spatial information on both the type and magnitude of hazards. Areas where one or more hazards occur are obviously less valuable for development than areas free from hazards. This is true even if the harmful effects may be corrected, because those corrective devices are usually very costly and often ineffective. In short, the assessments of special-value resources and hazards imply development restrictions in those portions of the metropolitan landscape where assessed values or hazards are high.

The development suitability component is the obverse of the previous two components. Its objective is to identify the most suitable areas for development from the point of view of physical, climatic, and visual characteristics. Highly suitable areas for development are less costly to build upon and provide increased amenities and comfort when developed.

The ecological stability component represents another essential consideration. Exploration of special resource-value areas, such as gravel quarries, production of environmental hazards such as air pollution, and even extensive development on highly suitable lands may have greater negative effects on the metropolitan ecosystem than desired. A preliminary objective of this component is to determine the amount and distribution of land uses in what Odum *(1969)* terms "protective", "productive", "compromise" (suburban), and "urban-industrial" zones. One purpose of this classification would be to understand the structure and function of the land uses within these zones. (The research in this component began only recently and as yet is not as developed as that of the other components.)

Detailed analysis and substantiation of values is conducted at the variable and subvariable level of phase I (fig. 2). Although original research to substantiate values is infrequently conducted, normally the team is dependent on the research finding of other scientists. For example, in the case of the *physical variable* of the development suitability component, values have been derived from the work of environmental geologists such as Flawn *(1970)*, scientists of the Soils Conservation Service *(Bartelli et al. 1966)*, or cost estimates of builders *McKeever 1968)*.

From these kinds of research results, the significance and magnitude of such subvariables as degree of slope or depth to water table for various developments are estimated. The resulting suitability assessments are analyzed in regard to short-range effects on construction costs to the developer, and long-range effects of these costs both to the community (e.g., in the form of siltation problems) and to the occupant (who in the case of high water table, would frequently need to pump water out of his basement.)

PARTIAL APPLICATION OF THE ASSESSMENT PHASE

Before we discuss the results of the application and synthesis of qualitative environmental assessments, a discussion of the preparation of data used in the step-by-step procedure used in the COMLUP computer manipulation is desirable. As mentioned earlier, the Computer Mapping for Land Use Planning (COMLUP) system of USDA Forest Service is the system used and adopted in the assessment phase.

DATA Preparation and the COMLUP Process

All of the assessment procedures in all of the assessment components are essentially composed of two elements: pregathered data in mapped form and the manipulation of those data according to a defined metric. The data are obtained from reliable sources. For example, the Soil Conservation Service supplies detailed soils maps or the U.S. Geologic Survey provides data obtained from aerial photogrammetry and ground truth validation.

These data are termed source maps for the purposes of the METLAND study. They are manipulated and aggregated in different ways according to the precise requirements of each assessment variable and its metric needs. Nevertheless, the procedure for the preparation of these source maps for manipulation, the actual procedure for manipulation, and the procedure for the final plotting of variable assessment maps is common to all. That procedure is basically as follows:

STEP 1: Digitize, edit and store on magnetic tape all the information contained on the source maps. (This is the function of the first third of the COMLUP programs.)

STEP 2: Aggregate the digitized source-map data according to the needs of the variable or subvariable assessment procedure, and make any overlays that are required by that procedure. (Second third of COMLUP.)

STEP 3: Plot the results. (Final third of COMLUP.)

Internally the COMLUP programs take the digitized data in line-segment form and overlay a grid of extremely fine granularity (500 x 1000 cells) on those data. With the data in this gridded format, the overlays required in Step 2 may be made with no difficulty. Step 3 reconverts these data to line format so that they may be plotted on a drum or flat-bed plotter. It would also be possible to use some of the newer plotting techniques such as three-dimensional plotting of the SYMVU type if desired.

Some Composite Results and Planning Considerations

Of the four components noted above, the special-value-resource component was selected to illustrate the resuts of synthesizing the assessment values. Assessments utilizing the COMLUP technique were prepared for four special-resource-value areas: agricultural productivity, wildlife productivity, water resources, and sand and gravel. These were composited for two points in time — 1952 and 1971 *(Fabos 1973)*.

Early landscape-planning procedures simply identified landscape values or hazard potentials. When they were thought to be significant they were handled as co-equals (each having equal importance). Resulting high- and low-value areas could be depicted.

With the numerous problems sure to beset us in the last quarter of this century, it will become increasingly difficult to defend environmental landscape values, when pressured for trade-offs by economical, political, and social values by simple statements such as high value, as concluded by the landscape approach. When making trade-off decisions, most commonly accepted values are expressed in monetary terms.

A pound of meat costs more than a pound of bread, even though both are of high value as food. Similarly, value differences exist among special environmental resources and all other categories discussed.

It ha been implied that these value differences can be based on social/political and economic values. Political decisions often express composite values of subgroups or interest groups of the society. Through survey research techniques and observation, planners can estimate the values of pertinent subgroups. Economists also have developed numerous procedures to distinguish among values.

In environmental planning, several sets of values should be established. Social/political and economic values should be expressed for both short-range and long-range goals. Though planners have experimented with this idea, prior to the advancement of the parametric planning approach, the adaptation of this concept to decision-making was not feasible. In the near future, however, the rapid computerized, quantitative information of the consequences of trade-offs among alternative sets of values will be readily available for decision makers.

To illustrate how a single-purpose value differentiation can provide an input to environmental/landscape planning, the value differences among the assessed special resources are shown in figure 3 in economic terms. The resource economists of the METLAND team (Foster, Torla, and Whaley) have provided value estimates for the resource, hazard, and development suitability variables listed under the heading phase I in figure 2.

The preparation of the composite special-resource-value map is similar to that used in the landscape approach. As a first step, high yield and quality water-resource areas, high-quality and usable agriculture lands, areas of high-quality wildlife, and areas with good sand and gravel potential were located and mapped.

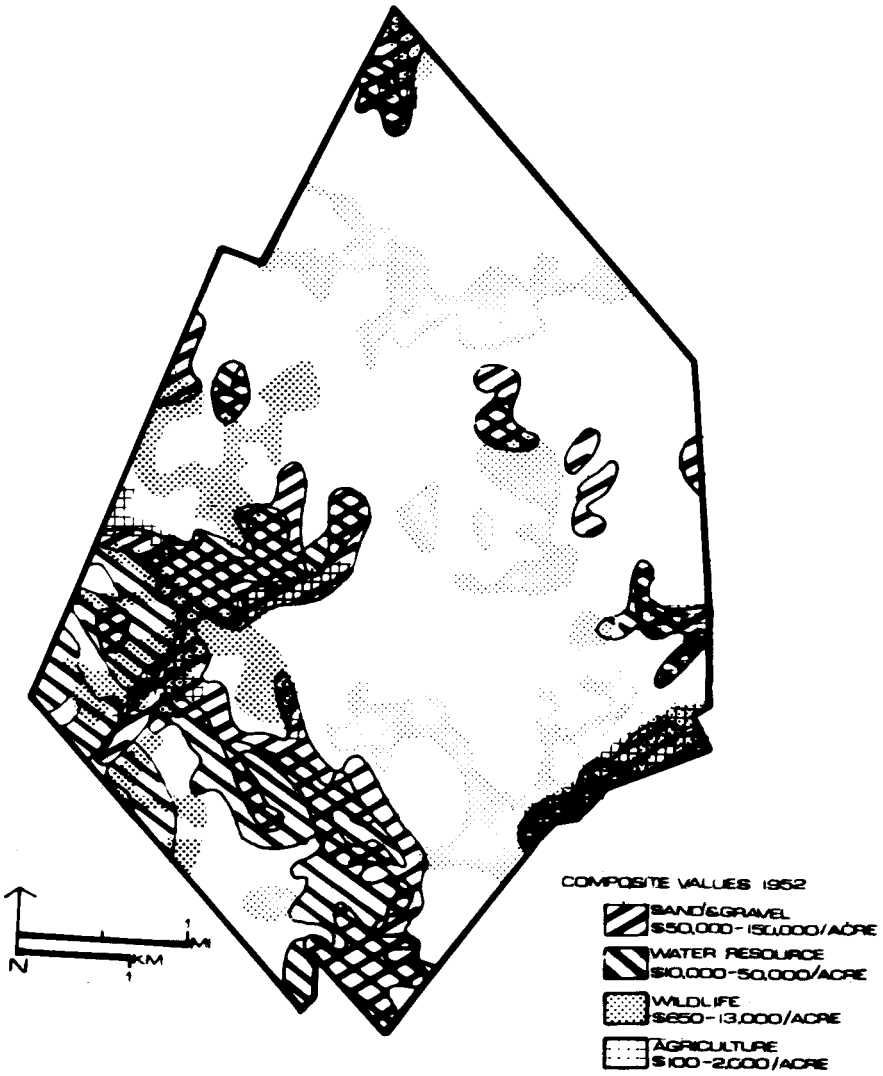
The difference between this and the landscape-planning approach, however, is twofold. First, the overlaying process is done rapidly and accurately by computer; and second, each area with high values may be assessed in terms of the estimated combined dollar value of the resource present.

Because of the scale of the maps presented in figure 3, the composite map has been simplified for visual display. Instead of the actual estimates, only ranges from low to high values are shown. The computer, however, is capable of calculating the composite estimate values per acre or per parcel of each combination.

The composite values of the special resources shown in figure 3 are most impressive. If these values, which are estimates, were confirmed, the cost of metropolitan growth, when implemented without regard to environmental values, would be shown to be very high indeed. The reader is cautioned, however, not to take these value estimates as conclusive evidence of resource loss. A more appropriate use of this information lies in two areas. First, when probable areas of resource-value concentration are known, growth can be directed away from these areas, assuming that sufficient alternative land is available. When and if at a later date these values are confirmed by detailed assessment techniques, such as drilling to find out actual depth and quality of sand and gravel resources, more permanent management decisions may be made for their use.

A second consideration in the use of this information lies in the recognition that these overlapping values are not always additive. For example, excavation of sand and gravel in areas of high water-supply potential may impair the rechargeability of ground water or destroy certain wildlife-habitat areas. As

Figure 3.—This simplified composite special-resource-value assessment illustrates an application of the parametic approach to Burlington, Massachusetts. The values listed are estimates of 1952 composite resource values. These estimated values range from $100/acre to a possible $203,300/acre (where water, wildlife, agriculture, and sand and gravel resource areas overlap). Notice that a great portion of these valuable resource areas were developed by housing, commercial, and industrial uses from 1952 to 1971. The impact on these areas led to an estimated loss of over $30 million dollars in foregone special-resource value.



a result, the value of the area may not represent the sum of the value of each resource when considered individually.

The significant point to be gleaned from this information is that models are being constructed to examine these relationships and environmental/landscape parameters. The METLAND model illustrated here is a reflection of the dynamic nature of this new field. Both are growing rapidly in an effort to deal with the problem of decentralized metropolitan growth. The example illustrated here portrays an interim step, useful today, while the more sophisticated computer assessment techniques are being developed.

We believe that this new parametric

approach will provide better and more diversified information on the qualitative aspects of the environment to decision-makers. Resource qualities and quantities together, with their location and distribution patterns, may now be assessed and manipulated by this process which, we believe, is a significant improvement in the state of the art of physical/landscape planning.

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Use of the Delphi Method for Determining Community Growth Goals Inventory: The Nashville Experience

by VISHWA K. VARMA, *regional manager, American Consulting Services, Franklin, Tenn.; and was director, Environmental Review Office, Metropolitan Government of Nashville and Davidson County, Nashville, Tenn. when this paper was presented.*

ABSTRACT.—The author discusses the growth-inducing pressures on Nashville, Tennessee, describes the application of the Delphi technique to develop an inventory of the community's growth goals, and suggests that the development of a list of community goals is a necessary first step toward growth management.

GOALS AND THE CONCERN FOR THE FUTURE

HAVING A CONCEPT of the future and seeking a better tomorrow, man sets goals and then attempts to influence his environment toward attaining them. A goal is the beginning of a problem, in that a problem is an unmet goal. Without a goal, a problem does not exist.

Today the urban centers of America are faced with several unmet needs and unsolved problems. Problems of economy and ecology seem to loom larger than ever.

These problems exist in spite of the fact that an estimated 85 percent of all the scientists that have ever lived on earth are living in our day and age. These problems are in direct contradiction to the prophecy made in 1936 about life in 1960 and beyond *(Langdon-Davies 1936):*

> "... food, clothing, and shelter will cost as little as air ... and there will be room for all, rent free ... Science has only to go a few steps farther ..."

The concern for these problems is a concern for our future — and that of our children. Many cities in the U.S.A. are faced with this concern as they find a prematurely arrived future at their doorsteps.

THE SETTING IN NASHVILLE

In the United States, 75 percent of the people live on approximately 3 percent of the land — mainly in urban centers. Nashville, Tennessee, is one of these centers. The leadership of Nashville has voiced its concern for building a viable future for Nashville. They have asked themselves several questions. Do we, as a city, know what we want our future to be? Are we prepared for the future? For instance, in his 1974 state-of metro address, former Mayor Beverly Briley exhorted Nashvillians to "believe in and strive for a future we may not see," and announced the formation of a Nashville 2001 Citizens' Goals Committee.

Nashville has a consolidated city-county metropolitan type of government. It came into being in 1962, bringing with it a single government with county-wide jurisdiction instead of the six city governments that existed in Davidson County before consolidation.

Nashville is the capital city of Tennessee and the economic and population center of the 13-county Mid-Cumberland Development District. With a population of 460,000, Nashville accounts for 56 percent of the region's population. It is also the main trade center of the

Mid-Cumberland Region as well as its financial and medical services hub. It has a balanced and diversified economy of industrial and commercial development. Its tourist and entertainment traffic, based primarily on its reputation as "Music City, USA," will probably, increase after release of the movie *Nashville!*

In 1973 the Academy for Contemporary Problems projected Nashville to be one of 28 urban centers where 90 percent of the American population will be centered in the year 2000. Several developments are now taking place around Nashville that do indeed portend a substantial growth in and around it. In December 1972, construction began on the Tombigbee Waterway. This massive waterway, funded by federal funds and scheduled for completion in 1981, will in effect connect Alabama, Mississippi, Tennessee, and Kentucky to the Gulf of Mexico and hence to world markets. During the last year work has begun on a 3-billion-dollar nuclear power facility for the Tennessee Valley Authority. This power plant will be located in Hartsville, just 25 miles east of Nashville. With 13 major colleges and universities, 5 major hospitals, the bulk of the country music industry, and six legs of major interstate highways, Nashville is faced with inevitable growth in the coming years.

The choice, for Nashville's decision-makers, is not between growth and no growth, but rather between disorderly growth and managed growth.

NASHVILLE'S EXPERIMENT WITH THE DELPHI TECHNIQUE

This issue of growth has been addressed by many groups and organizations in Nashville and Davidson County during the past few years. In July 1972, an Environmental Planning and Management Project was started in Nashville with a grant from the Ford Foundation *(Felling 1974)*. The Project's objective was to develop a strategic environmental problem-solving capability in the local government system, while recognizing the citizens' increasing concern about not only the quantity of growth but also the quality of that growth.

Last year the Environmental Planning and Management Project attempted to develop an inventory of community goals. The objective of this experimental undertaking was to identify a series of goals as articulated by Nashville's opinion leaders. It was decided to use a modified Delphi technique to achieve this objective.

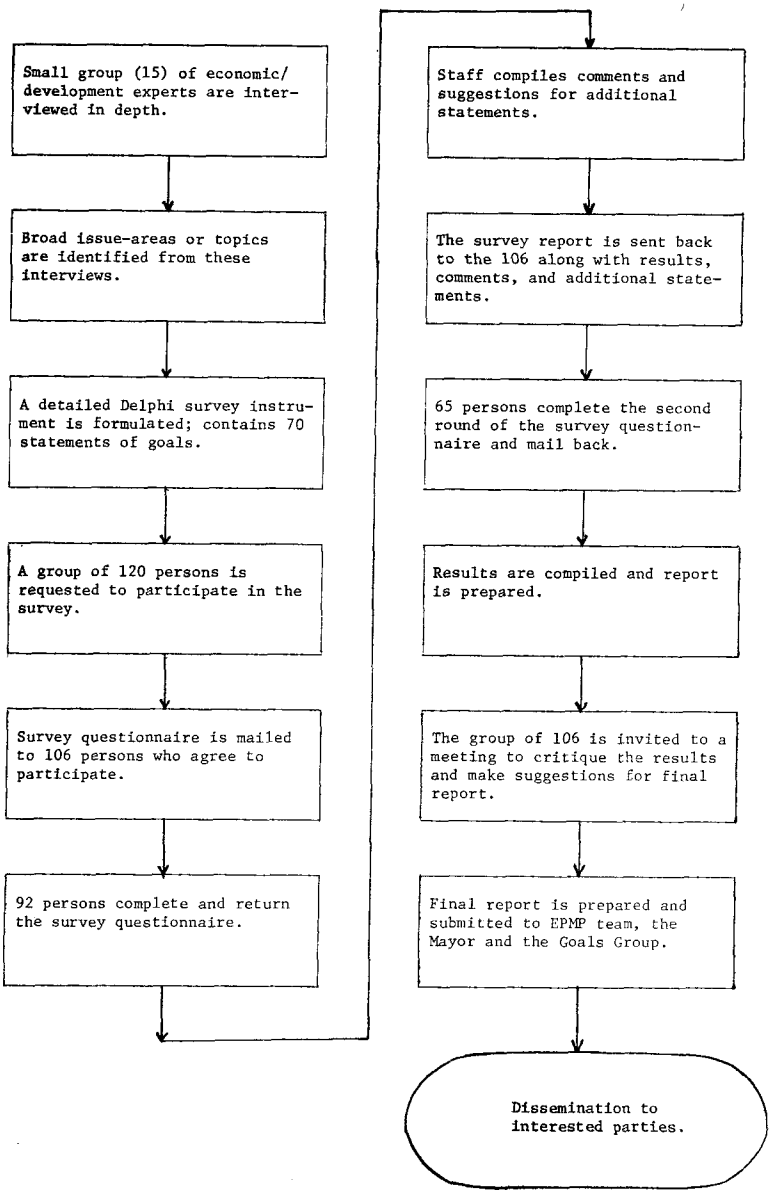
The most frequent use of the Delphi technique has been to obtain expert consensus about the likely time of occurrence of some future event. Lately, the term "Policy Delphi" has been used to describe experiments in which researchers have tried to identify policy options on general issues. The major difficulty encountered in such Delphi experiments is with the adequacy of the description of policies. A certain amount of generality or ambiguity is always inherent in these Delphi statements, and each expert's interpretations embellish it to the point that the statements are too general to be policy guides or too specific for a wide variety of experts to comment on.

In the Nashville experiment, the Delphi technique was used primarily to collect data in which the data-gatherer acts as an objective collator of the opinions of others. Specifically, the modified Delphi consisted of the following steps (fig. 1) :

Step 1.—A small group of 15 developmental experts was subjected to in-depth interviews. This group included economists, developmental experts, urban planners, elected officials, bankers, engineers, and investment experts. The interviews were taped and conducted by a retired newspaper reporter who had covered city affairs for the past 35 years. Open-ended questions were used. The purpose was to surface issues and aspects around the city's future.

Step 2.—A staff team conducted an

Figure 1.—Plan and sequence of the Delphi technique used in Nashville.



analysis of transcripts from Step 1. A list of broad issues and goal-type statements was developed. A detailed list of community goals, containing 69 statements, was developed.

Step 3.—A Delphi questionnaire was developed from the list of goals. The questionnaire sought responses on (1) the level of importance of a goal statement and (2) how much needs to be done to reach the goal. To obtain these two pieces of data, the respondents were asked to rate each goal on its present status and desired future status.

Step 4.—A group of 120 opinion leaders was invited to participate in this survey. The method of selection was as follows: The Mayor invited all profes-

sional associations, clubs, citizen bodies, civic groups, public interest groups, religious and business organizations, League of Women Voters, Sierra Club, etc., and the general citizenry to send him nominations for the Nashville 2001, Citizens' Goals Committee. More than 600 names were received. The project staff was allowed access to this list. After eliminating duplications and selecting for a cross-sectional representation, a list of 120 opinion leaders was selected. Of these 106 agreed to participate in the Delphi survey.

Step 5.—Delphi questionnaires were mailed to 106 persons.

Step 6.—The returns (92 out of 106) were tabulated, and step 5 was repeated. This time, respondents got summary results of how others rated the various goals and had a chance to revise their assessments. The returns were again tabulated and comments collated. The final report was prepared and presented to the Mayor and the Citizens' Goals Committee. After the first round, an additional nine goal statements were added on to the inventory of community goals.

RESULTS AND CONCLUSIONS

Through this process, 78 goal statements were generated. Each falls into one of the following areas:

1. Governance
2. Regional cooperation
3. Economic and community development
4. Recreational, leisure, and cultural resources
5. Public education
6. Human resource development
7. Transportation
8. Public safety/crime prevention/justice system
9. Environment
10. Housing

Overall mean scores after round two for these categories showed that housing, environment, and public safety were the top three issues. Also, if the

Table 1.—Overall mean scores and differences

Status	Environment	Housing	Transportation	Public safety	Public education	Human resource development	Recreational resources	Regional aspects & relations	Economic community development	Governmental services & concerns
					ROUND 1					
Desired	4.057	3.857	3.617	3.799	3.848	3.630	3.202	3.708	3.905	3.467
Present	2.726	2.333	2.350	2.514	2.385	2.457	2.557	2.393	2.677	2.171
Difference	1.331	1.524	1.267	1.285	1.463	1.173	0.645	1.315	1.228	1.290
					ROUND 2					
Desired	4.140	4.533	3.617	4.102	3.733	3.723	3.106	3.733	3.989	3.560
Present	2.746	2.288	2.350	2.673	2.706	2.486	2.700	2.570	2.818	2.208
Difference	1.394	2.245	1.267	1.429	1.027	1.237	0.406	1.163	1.171	1.352

Figure 2.—A comparative analysis of goals by ranking of differences.

COMPARATIVE ANALYSIS BY RANKING OF DIFFERENCES (D-P)	Ranking by mean of difference	Overall	PROFESSION				INCOME			LENGTH OF RESIDENCE			RACE	
			Government services	Retired and housewives	Business	Professionals	Low	Medium	High	Less than 10 years		More than 39 years	Caucasians	Blacks
2. HOUSING	(1)	1	1	2	1	3	1	1 -	3	4	1	1	2	1
	D / P	3 / 9	5 / 9	3 / 9	3 / 7	5 / 8	3 / 9	3 / 7	6 / 7	5 / 7	5 / 9	1 / 8	5 / 9	1 / 10
5. PUBLIC EDUCATION	(9)	2	3	1	5	2	2	3	2	3	3	2	1	3
	D / P	4 / 7	3 / 7	1 / 10	6 / 8	1 / 6	2 / 7	4 / 6	3 / 10	3 / 6	3 / 7	4 / 9	3 / 8	2 / 4
1. ENVIRONMENT	(3)	3	6	3	3	6	6	8	1	6	2	8	4	10
	D / P	1 / 1	2 / 1	2 / 4	1 / 1	4 / 3	1 / 2	1 / 1	1 / 8	1 / 1	1 / 6	2 / 1	1 / 1	8 / 1
8. REGIONAL ASPECTS AND RELATIONS	(8)	4	2	4	8	1	5	2	9	2	6	4	5	7
	D / P	6 / 6	1 / 6	5 / 7	8 / 5	2 / 9	6 / 8	6 / 9	7 / 2	4 / 8	6 / 6	6 / 7	6 / 6	9 / 8
4. PUBLIC SAFETY	(2)	5	5	7	6	5	4	6	4	8	4	3	3	6
	D / P	5 / 4	6 / 4	6 / 6	4 / 4	3 / 4	5 / 5	5 / 5	5 / 5	7 / 5	4 / 4	5 / 4	4 / 5	6 / 6
3. TRANSPORTATION	(5)	6	7	9	2	8	8	4	8	1	9	6	8	5
	D / P	8 / 8	9 / 8	8 / 2	5 / 9	8 / 7	8 / 6	8 / 8	8 / 4	6 / 7	9 / 8	7 / 6	7 / 7	7 / 7
10. GOVERNMENT SERVICES AND CONCERNS	(4)	7	4	5	7	4	3	5	7	5	5	7	6	2
	D / P	9 / 10	7 / 10	9 / 10	9 / 10	9 / 10	9 / 10	9 / 10	9 / 10	9 / 10	7 / 10	9 / 10	9 / 10	5 / 9
9. ECONOMIC COMMUNITY DEVELOPMENT	(7)	8	8	8	4	9	9	7	5	7	7	5	7	8
	D / P	2 / 2	4 / 2	7 / 1	2 / 2	6 / 2	4 / 1	2 / 2	2 / 1	2 / 2	2 / 2	3 / 2	2 / 2	3 / 2
6. HUMAN RESOURCE DEVELOPMENT	(6)	9	9	6	9	7	7	9	6	9	8	9	9	4
	D / P	7 / 5	8 / 5	4 / 5	7 / 3	7 / 5	7 / 4	7 / 4	4 / 3	8 / 4	7 / 5	8 / 3	8 / 3	4 / 5
7. RECREATIONAL RESOURCES	(10)	10	10	10	10	10	10	10	10	10	10	10	10	9
	D / P	10 / 3	10 / 3	10 / 3	10 / 6	10 / 1	10 / 3	10 / 3	10 / 6	10 / 3	10 / 3	10 / 5	10 / 4	10 / 3

difference between desired status and present status is used as a measure of how far we've got to go to get where we want to be, even then the same three issues are on top. This time, however, the order is slightly different: housing, public safety, and environment (table 1).

A more detailed analysis was done on the basis of (1) profession, (2) income, (3) length of residence in Davidson County, and (4) race (fig. 2). For Blacks, housing and governmental services were the most important goal areas, as measured by the mean difference between present and desired status scores. By the same measure and for the same group, environment ranked tenth, while its rating by the total group was third.

In transportation, the two subgroups that attach high importance (by mean of difference between present and desired) to this are (1) businessmen and (2) relative newcomers to the community.

The main accomplishment of this experiment was the starting of a community-based process for looking at Nashville's future. It has developed an awareness for goal-setting as a basis for growth-management.

True, the survey itself was not as statistically clean as a researcher might have desired it to be. But then, it was undertaken by practitioners, not academicians. Consequently, there are several caveats. The most important, of course, is the admonition that the dynamics of the process were more important than the output. More time could have been spent on making the statements more substantive.

The Delphi technique has tremendous value as an educational device for planners, particularly policy planners. That is its prime benefit in Nashville. It obviously obtained citizen input through a very representative group. In fact, it could be expanded to cover wider segments of population.

The technique may have more use if used on an ongoing basis. Goals should not be considered one at a time, nor should they be thought of as set for all time to come. Goals are as dynamic as the human experience. As goals are reached, visions are broadened and yet more difficult and numerous goals are set.

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Techniques of Data Analysis and Presentation for Planners of the Metropolitan Environment

by JOELEE NORMAND, *Department of Meteorology, University of Oklahoma, Norman, Okla.*

ABSTRACT.—Relationships between the characteristics of the physical environment of a metropolitan area and the activities of its human inhabitants can be used to predict probable future dynamic trends, both demographic and environmental. Using simple linear regression, we were able to highlight several dynamic features of the metropolitan area of Tulsa, Oklahoma. Computer movies of the growth of Tulsa and attendant air-pollution problems were used for showing demographic and physical features simultaneously to facilitate the information-assimilation process so critical to planning.

THE NEED FOR ASSIMILATION of large quantities of data is critical to decision-makers in metropolitan environmental planning. The rapid and effective transfer of technology from the scientific and engineering fields to the urban-planning field is the purpose of the studies presented in this paper.

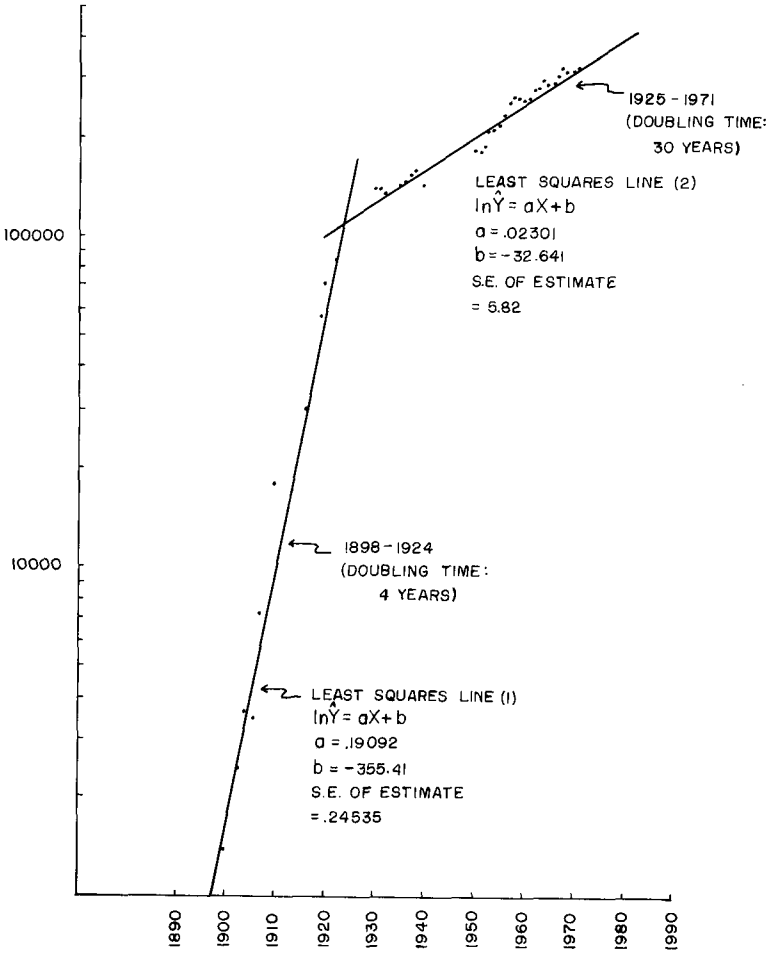
ANALYSIS OF THE GROWTH OF TWO CITIES

The understanding of past and present dynamic trends is required for successful urban planning if we are to make future growth more orderly and less chaotic, more useful to mankind and less wasteful of resources. Improving communication between disciplines that already make wide use of analytical tools and those just beginning to make use of such tools for solving problems of human settlement provided the impetus for a study. An attempt was made to collect data from the metropolitan areas of Oklahoma City and Tulsa, Oklahoma, which represent a 100-year time span (fig. 1). These data were the basis of an analysis and comparison of the growth trends in these two cities *(Normand 1975)*. The analysis technique used was that of regression of the data on time. Efforts to plot the data on a linear graph produced the usual poor fit to a straight line; however, when regression was performed on the log of the data, results represent familiar growth curves (fig. 2 and 3).

The analysis produced some interesting highlights of the characteristics of the two cities. For example, the consumption of electricity in Tulsa doubles every 8 years while the population has doubled only every 30 years since about 1922. The fact that Tulsa continues its use of electrical power at a rate almost four times faster than that of population growth points out a higher per-capita use of power at an ever-increasing rate. In both cities the population growth rate changed drastically in the 1920s. Tulsa's population doubled about every 4 years until 1922, then changed rate and has since doubled every 30 years. Oklahoma City's rate changed from a doubling time of 7 years to 30 years.

Such a change is attributed by some to oil boom years. However, the difference in character of the two cities is much better illustrated by graphs on economic indicators and employment. The highlights of population growth versus energy consumption illustrate a fast-approaching time when decisions will have to be made on proper resource allocation on a private and public scale.

Figure 1.—Population growth of Tulsa, Oklahoma. Regression of log Y on X.



This type of study could perhaps remove some barriers to interdisciplinary communication and utilization of analytical techniques in a practical application in metropolitan/environmental planning.

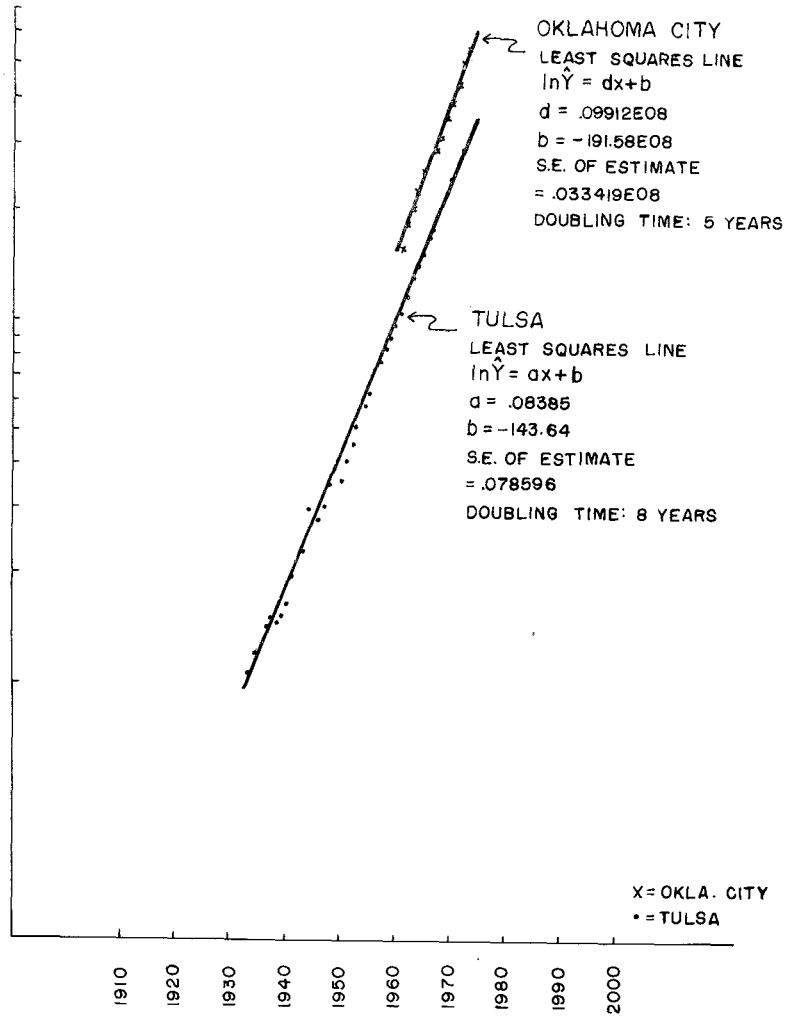
COMPUTER MOVIE OF THE GROWTH OF TULSA

In a text used by students of urban planning it is stated that "planners are ultimately interested in making statements about the relationships between key variables as they may or should exist at some future time. In order to make such statements, planners study the past and present conditions of the factors relevant to a given situation" (Goodman and Freund 1968).

Visualizing the evolution of the metabolism of a city is required in order to understand the character of its growth in the past and to plan for its future. With this idea in mind, data were collected from several metropolitan areas in Oklahoma for use in analysis of past and present trends, and for use in graphic presentation constructed by computer techniques.

One result of this project has been a computer movie of the growth of Tulsa *(Brady et al. 1975)*. In it are depicted the physical annexation process, from the original townsite to its present configuration. In addition, the demographic features are illustrated on linear graphs showing some of the dynamic

Figure 2.—Consumption of electricity (in millions of kilowatt hours) in Tulsa, Oklahoma. Regression of log Y on X.

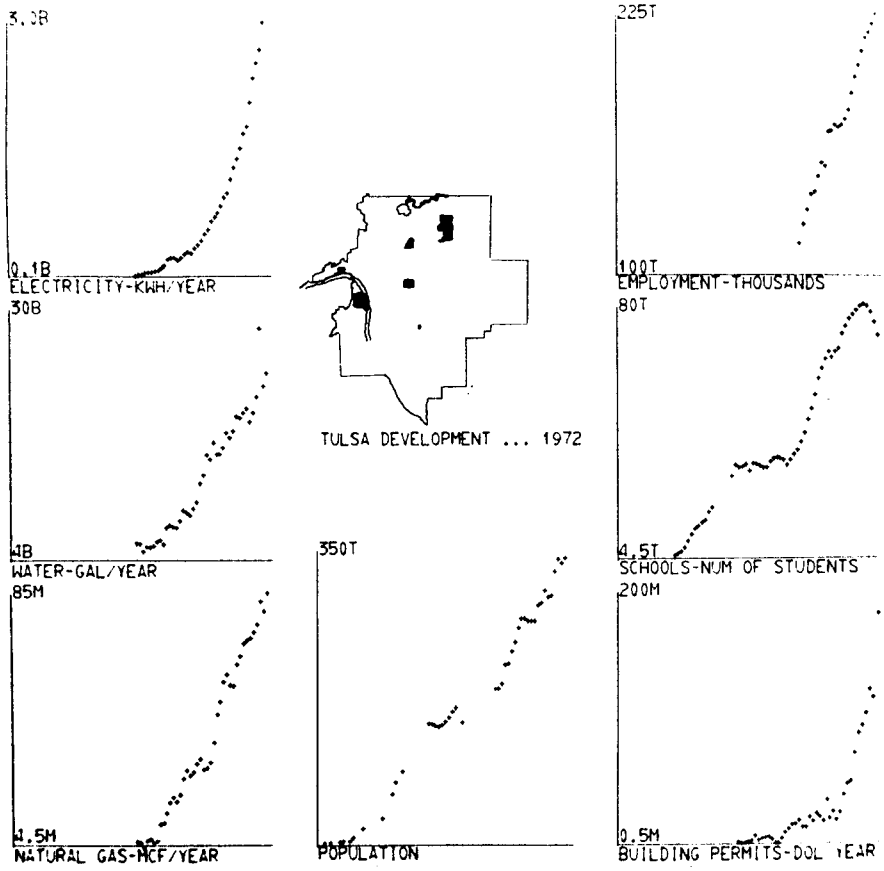


trends in this city: population growth, energy consumption, employment patterns, school enrollment, etc. (fig. 1 and 2). As a method for transferring techniques widely used in the scientific fields to that of planning for social needs, these computer graphic presentations have been found to be readily assimilable by the decision-maker as well as the ordinary citizen who has not had time to become algebraically oriented *(Eddy 1974)*.

FORECASTING DEMAND FROM PROPOSED DEVELOPMENTS

Evaluation of the impact of new developments in a community is another source of concern to urban decision-makers. Those agencies responsible for approving zoning and platting of proposed developments, in particular, find it necessary to make approvals for new developments without the assurance that public utilities and services such as water, sewers, and public schools will

Figure 3.—Computer movie of the growth of Tulsa, Oklahoma.



be available to adequately serve those developments after completion. The environmental impact is also many times left in question. The Proposed Development Sub-File is designed to provide a relatively accurate and rapid computerized system of predicting the needs and impacts of such developments *(Tulsa City-County Health Department 1972)*. The ability of this system of comparative computer programs to accumulate the anticipated impacts of all proposed developments (from the early stage of zoning change to completion) is of great advantage. The data system will be of benefit to government agencies by aiding planning for utility expansions and school facilities and in assessing housing trends and availability of services.

Those who invest in such developments may also benefit from this project, as it will be capable of serving as an early warning system in predicting probable future difficulties with existing facilities in the earliest stages of planning, and, therefore, modification or delay of development before the financial commitment has been further expanded. The system will provide reasonably accurate estimates of the effect of all proposed developments and existing developments on sewage-treatment plants, water plants, sources of water, public schools, solid-waste-disposal facilities, and environmental quality. A sample of the output expected for presentation to the decision-making bodies is presented here (fig. 4) as well as the predicted

Figure 4.—Impact of a proposed development on services and utilities.

WATER TREATMENT CAPACITY ASSESSMENT

COUNTY: TULSA

FACILITY: TULSA MUNICIPAL SYSTEM	AVE	PEAK
EXISTING TREATMENT CAPACITY	100 000 000	136 000 000
EXISTING DEMAND	64 400 000	117 000 000
REMAINING CAPACITY	35 600 000	19 000 000
PLATTED COMMITMENT	2 880 000	4 320 000
REMAINING CAPACITY	32 720 000	14 680 000
PRESENT ZONING COMMITMENT	8 640 000	12 960 000
REMAINING CAPACITY	24 080 000	1 720 000
PROPOSED ZONING DEMANDS		
Z 4701 CS	10 500	15 750
Z 4702 CS	35 000	52 500
Z 4706 CG OL	5 890	8 835
Z 4707 CS	56 000	84 000
Z 4712 CS OL RM-1 RD RS-3	425 200	637 800
TOTAL ZONING DEMAND	532 590	798 885
REMAINING CAPACITY	23 547 410	921 115
FUTURE DESIGN CAPACITY	110 000 000	145 000 000
YEAR: 1978		

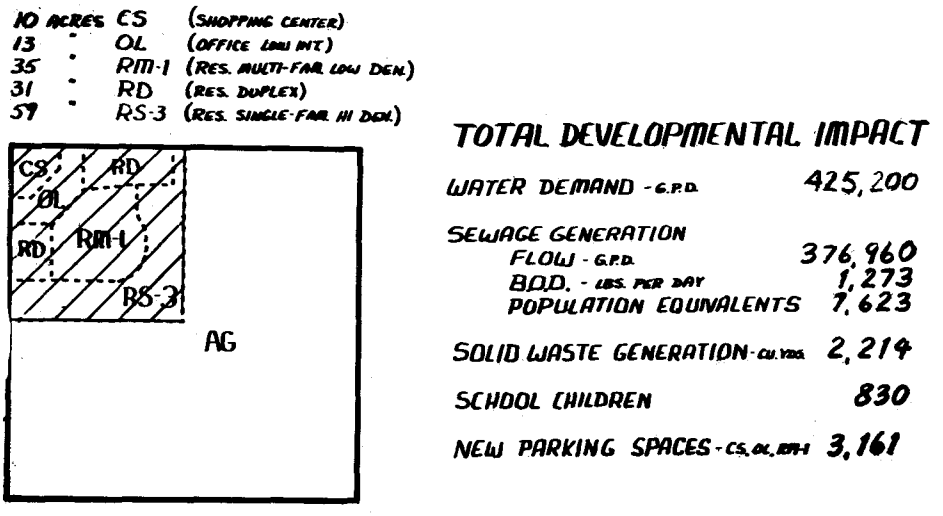
FACILITY: BROKEN ARROW PLANT

COUNTY: CREEK

WATER SOURCE ASSESSMENT

SOURCE: SPAVINAW	AVE	PEAK
RELIABLE YEILD	65 000 000	65 000 000
EXISTING DEMAND	64 400 000	117 000 000
REMAINING YEILD	600 000	-52 000 000
PLATTED COMMITMENT	2 880 000	4 320 000
OVERLOAD	-2 280 000	-47 680 000
PRESENT ZONING COMMITMENT	8 640 000	12 960 000
OVERLOAD	-10 920 000	-60 640 000
PROPOSED ZONING DEMANDS		
Z 4701 CS	10 500	15 750
Z 4702 CS	35 000	52 500
Z 4706 CG OL	5 890	8 835
Z 4707 CS	56 000	84 000
Z 4712 CS OL RM-1 RD RS-3	425 200	637 800
TOTAL ZONING DEMAND	532 590	798 885
OVERLOAD	-11 452 590	-61 438 800

Figure 5.—Sample output of proposed development system, showing assessment of demands on water treatment and water source.



impact of a hypothetical development as it would be assessed by this system (fig. 5).

AIR-POLLUTION MODELS AND COMPUTER MOVIES

Several existing air-pollution models have been adapted to the air-quality conditions in the Tulsa area. An illustrative sample of the Climatological Dispersion Model *(Busse and Zimmerman 1973)* is presented here. An annual average of ground-level concentrations of pollutants from both point and area sources is obtained by using this model. By using the original program, receptor points can be located to pinpoint concentrations of two pollutants at a time.

In addition, program modifications have made it possible to map concentrations of pollutants at locations arranged in a grid of specified size, rather than individual receptor sites, as reported by Normand *(1975)*. The unit area of 1 square mile was chosen to conform to the grid pattern of the major streets of Tulsa. The concentration estimate is made for receptors located at the center of these square-mile areas. A cross-section of the grid along a north-south column is shown here (fig. 6), for the effluent SO_2. This display of pollution concentration is an aid to visual perception of the dispersion of air pollution over a city-wide area. This method can be used by urban planners in assessing the impact of new industrial location on an annual basis.

Another model, which takes into account the differentiations in terrain of an urban area, as well as time and space variations in the wind field and stability of atmospheric conditions, is the Diffusion Wind Atmospheric Dispersion Model developed by Shannon *(1974)*. This is a four-dimensional model (X, Y, Z, T). The grid is vertically divided into eight layers, with a horizontal grid-mesh size of 1 square mile. Wind stability and effluents vary in space and time (fig. 7 and 8). A three-dimensional computer movie has been made *(Shannon 1974)* of the output of this model, showing a cloud of pollution moving across an urban area. The pollutants and stability are varied at 5-minute intervals.

This model permits the examination of the frequency distribution of various pollutants on different space-time scales.

Figure 6.—Cross-section of grid showing concentrations of SO_2 predicted by climatological dispersion model.

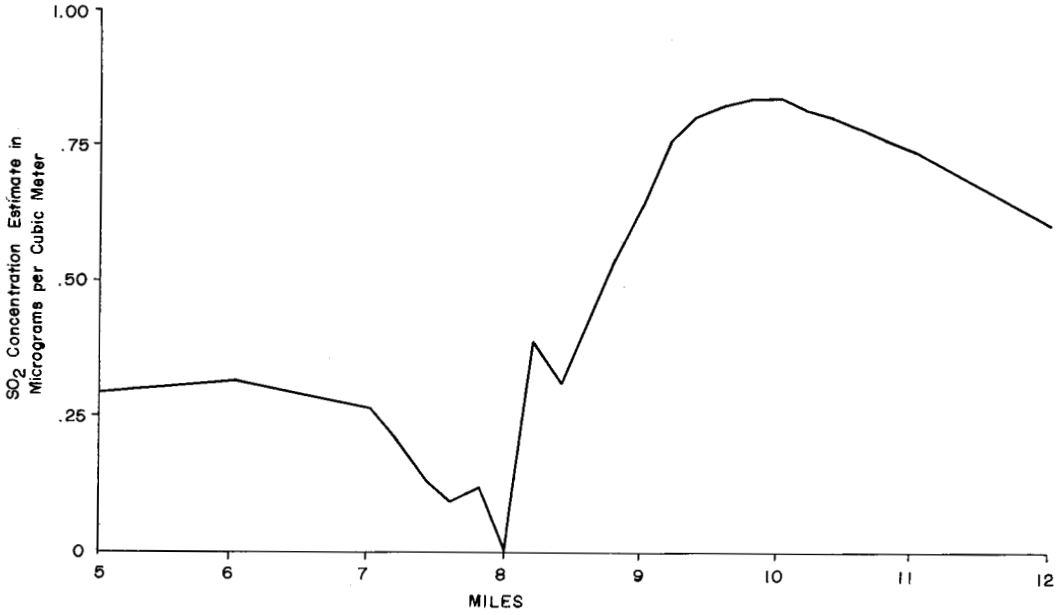
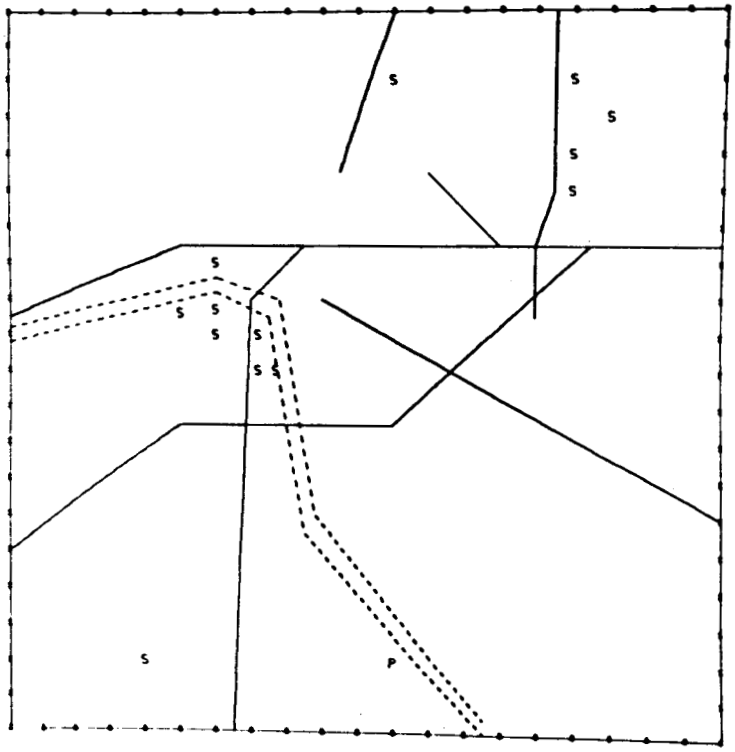
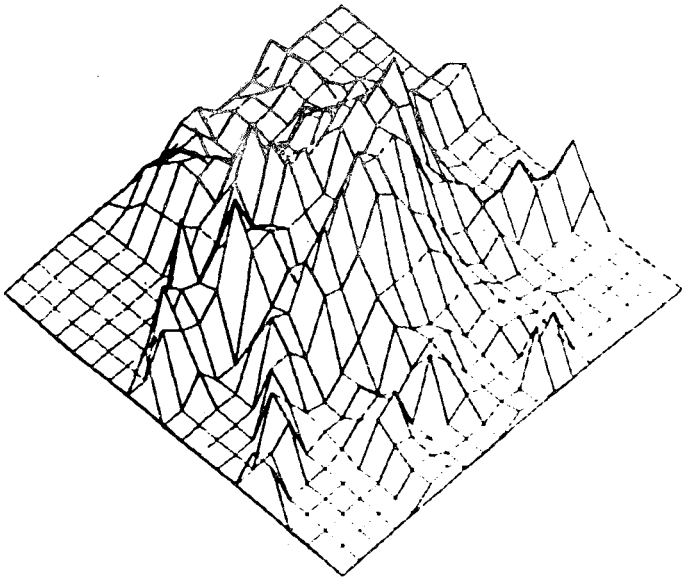


Figure 7.—Tulsa industrial point sources, future electrical generating plant site, freeways (output from diffusion wind atmospheric dispersion model).



TULSA INDUSTRIAL POINT SOURCES (S), FUTURE ELECTRICAL GENERATING PLANT SITE (P), FREEWAYS (SOLID LINES), ARKANSAS RIVER (DASHED LINES)
GRID INTERVAL ONE MILE. TOP IS NORTH

Figure 8.—Hydrocarbon emissions from current traffic (Kg./sq. mi./day).



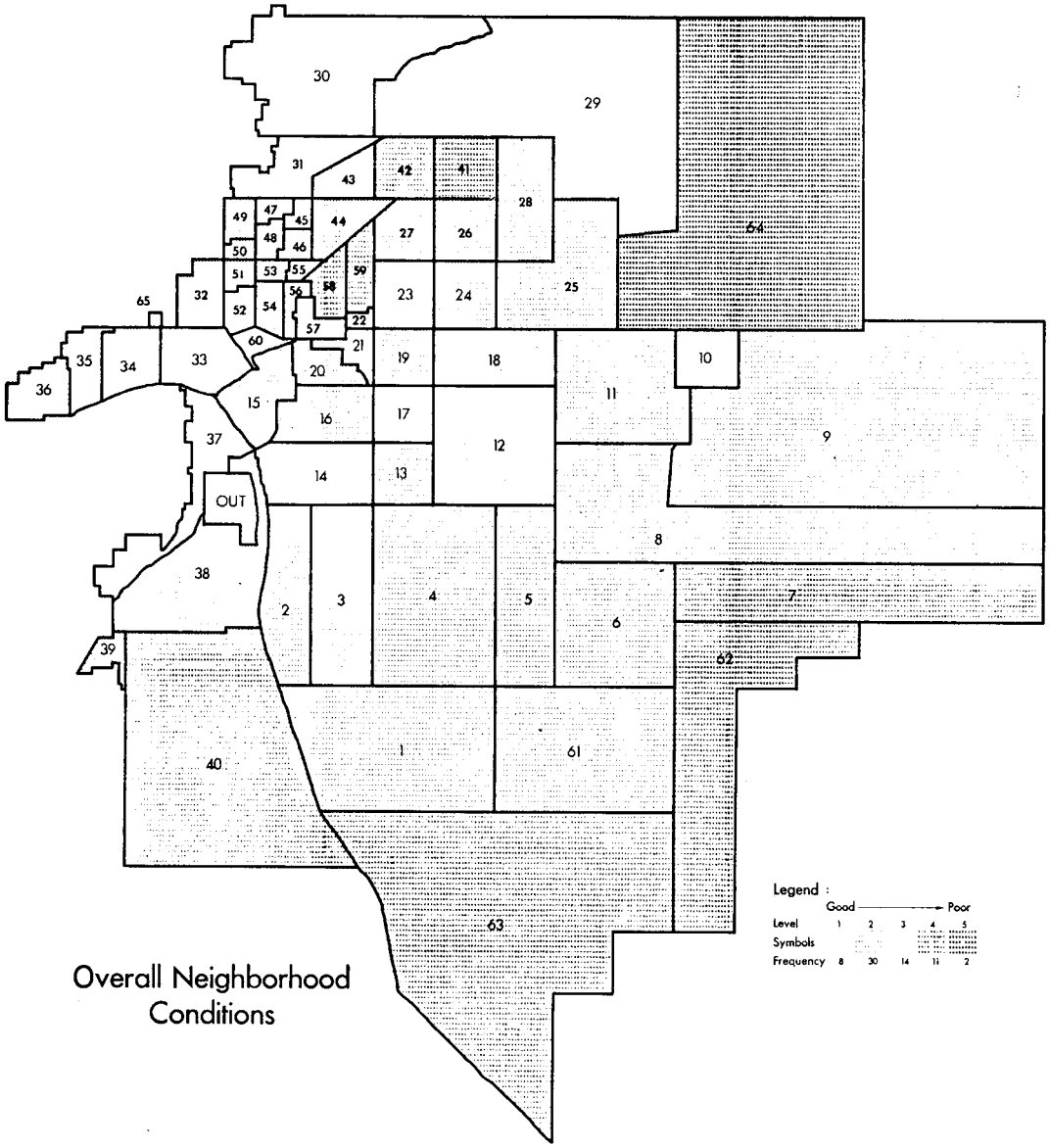
Optimal placement of monitoring sensors, as well as prediction of the impact of new industrial sites are two of the possible applications of this model for the planner of the metropolitan environment. Computer-produced movies of air-pollution patterns have proved very valuable for transferring large amounts of technical information in an easily assimilable format to nontechnical decision-makers in a short time.

ENVIRONMENTAL DEFICIENCIES VERSUS DEMOGRAPHIC CHARACTERISTICS OF A CITY

Evaluation of physical environmental deficiencies in relation to the characteristics of the population was the subject of another report. Data collected by the Tulsa City-County Health Department was selected for the study. Several computer programs that employed statistical techniques were used. Multiple linear regression and stepwise regression were used, and the relationships found are reported by Normand *(1974)*.

In a more extensive study by the Tulsa City-County Health Department, the whole area of Tulsa was surveyed, and many other variables were considered, employing the Neighborhood Environmental Evaluation Decision System (NEEDS), developed by the Bureau of Community Environmental Management of the Health Services and Mental Health Administration, U. S. Public Health Service. The statistical methods used in this survey were correlation analysis, factor analysis, cluster analysis, and regression analysis. An evaluation was made of complex combinations of interrelated conditions occuring in the living environment of specific areas of the community. Fig. 9 shows the ranking of overall neighborhood conditions, as one of the many variables analyzed. The net result of this study was to produce a statistically logical set of planning districts, each one of which

Figure 9.—Overall neighborhood conditions from NEEDS study in Tulsa, Oklahoma.



contained homogeneous attributes that distinguish it from its neighbors.

SUMMARY

Experts employed to solve the problems facing the metropolitan areas today are faced with dilemmas. One is the language barrier between different disciplines. The transfer of information and technology is the first obstacle to overcome. Some techniques of data assimilation that can be used to overcome the communication problem have been presented in this paper. An attempt has been made to show some techniques employed now by the sciences, which could be used to provide accurate and instantaneous presentations of consequences of past and possible future actions by the administrators of metropolitan areas. The rapid pace at which change occurs is highly visible in large urban

concentrations. The technology is available to show alternative methods of resource allocation to accommodate changes, and it is hoped that this effort will provide encouragement to the planners of metropolitan environment to make use of such techniques.

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- Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
- Warren, Pennsylvania.

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*1977. **Proceedings of the Conference on Metropolitan Physical Environment.*** Northeast. For. Exp. Stn., Upper Darby, Pa.
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A report on the conference held in August 1975 at Syracuse, N. Y., containing 50 papers presented at the meeting, at which some 160 scientists and scholars discussed the use of vegetation, space, and structures to improve the amenities for people who live in metropolitan areas.

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