Use of a Land-use-based Emissions Inventory in Delineating Clean-air Zones

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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.

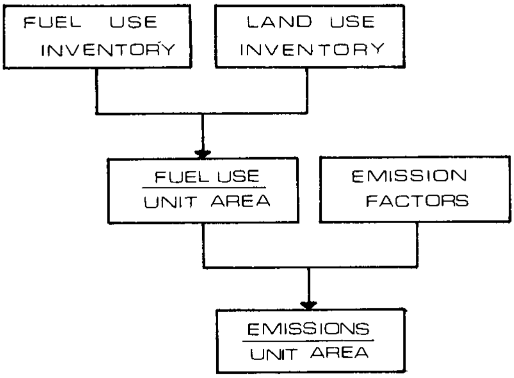
After a land-use-based emissions inventory was established, a model was developed to use that data for delineating clear air (buffer) zones around area sources.

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 nonfuel 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.

Figure 1.—Procedure for establishing a land-use-based emissions inventory.



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.

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)	
Mining or waste-disposal areas (5)	
Agricultural and open lands (11)	Other
Forest lands (40)	
Wetlands—except open fresh water (10)	
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 (incliung 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:

$$C = \frac{Q\,(10^6)}{\pi\,\sigma_y\sigma_z\,u}\exp\left[-\tfrac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]\left(\frac{Tk}{Ts}\right)^{.20} \qquad [1]$$

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:

$$C/Q = \frac{(10)^6}{(3.14)\,\sigma_y\sigma_z\,(2)} \exp\left[-\tfrac{1}{2}\left(\frac{20}{\sigma_z}\right)^2\right](.37) \qquad [2]$$

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

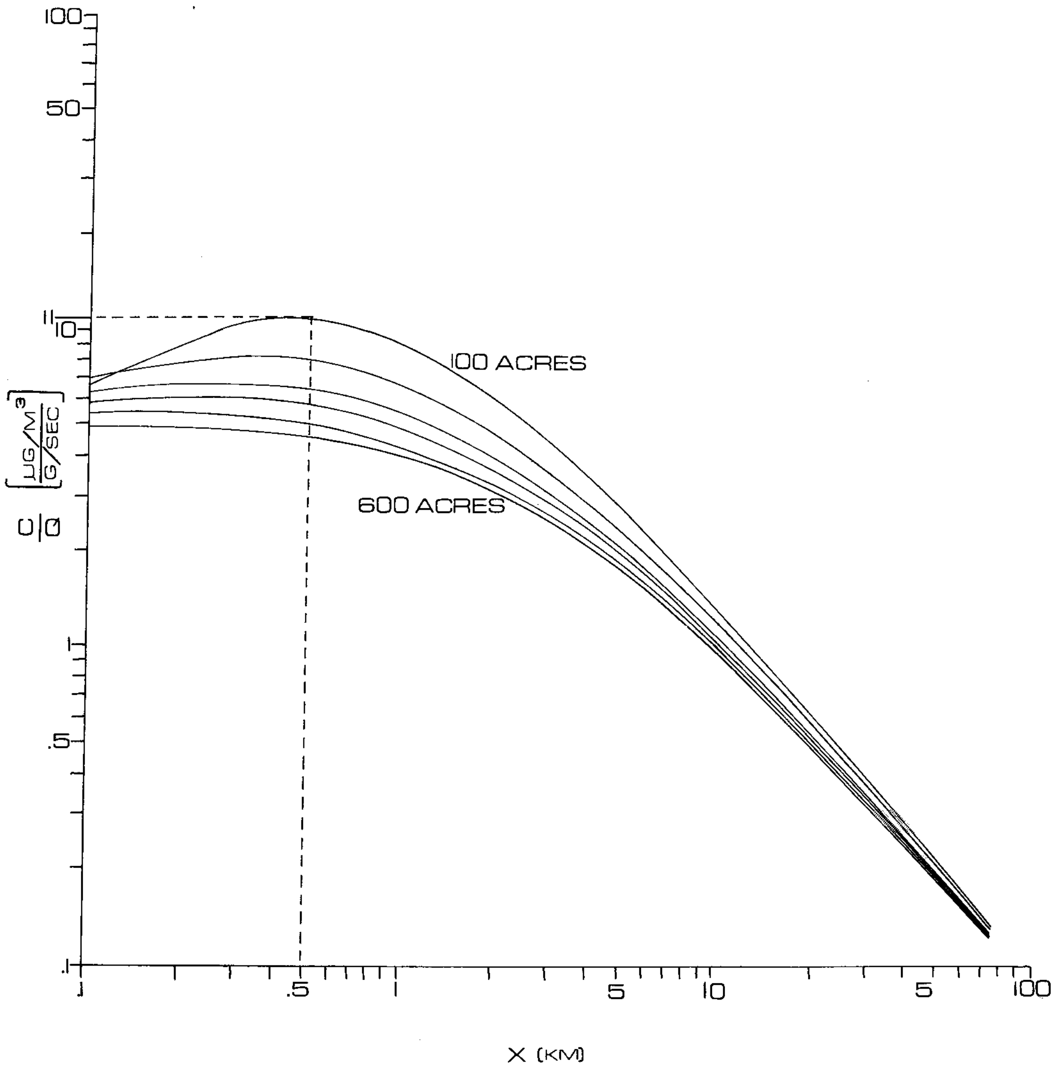
A graph of C/Q versus distance from the edge of the source can be plotted for various acreages. Such graphs (on log-log scales for clarity) were plotted for acreages of 100 to 600 acres (fig. 2).

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:

$$Pm = \frac{P \text{ x } \left(\frac{6300}{4600}\right)}{P \text{ x } \left(\frac{6300}{4600}\right) + (100\text{-}P)} \qquad [3]$$

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:

$$Q = .267 \text{ g/sec-acre} \times 105 \text{ acres} = 28.0 \text{ g/sec} \qquad [4]$$

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:

$$Q = .135\ g/sec\ X\ 105\ acres = 14.2\ g/sec \quad [6]$$

$$C/Q = \frac{285\ ug/m^3}{14.2\ g/sec} = 20.1 \frac{ug/m^3}{g/sec} \quad [7]$$

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.

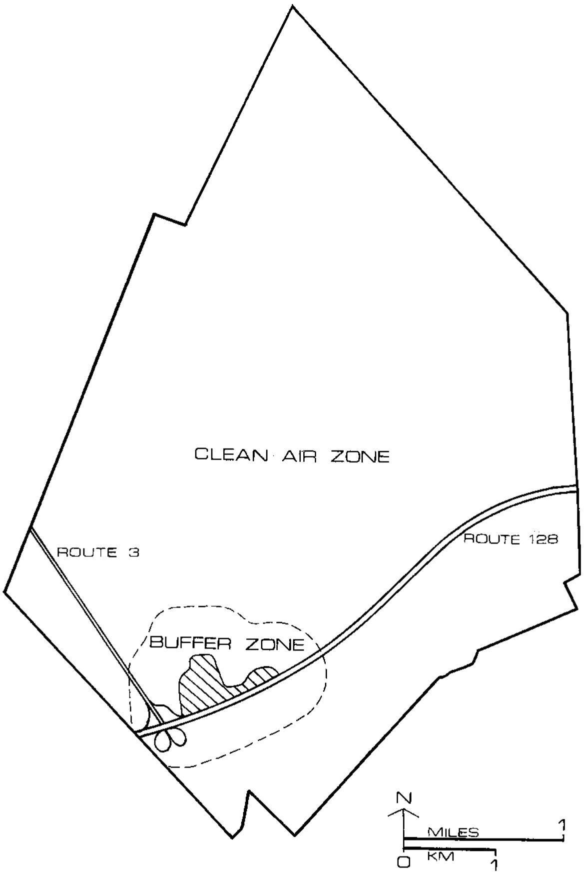
All of the above recommendations are made in the absence of actual air-sampling data. Planning decision may be changed should sampled concentration data become available.

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 onsite 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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