# HYDROLOGIC EFFECTS *from* URBANIZATION *of forested watersheds in the Northeast*

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# HYDROLOGIC EFFECTS *from* URBANIZATION *of forested watersheds in the Northeast*

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## A CHANGING ENVIRONMENT

URBANIZATION, particularly in the crowded Northeast, has created a new environment. Asphalt and concrete have replaced hundreds of square miles of soil, buildings have replaced trees on much of the land, and sewers have replaced streambeds in many areas. As a result, the hydrology of this land is changing rapidly.

To determine the effects of this expanding urbanization on forested watersheds, the Northeastern Forest Experiment Station has studied streamflow records of forested and urbanized watersheds. This paper is a report of that study.

We consider first the urban and forest environments in relation to their differing effects on several hydrologic processes and on water quality. Second, we estimate the effects of urbanization on evapotranspiration and runoff by theoretically imposing urban conditions on a forested watershed for which climatic and streamflow records are available. Third, we describe the effects of actual progressive urbanization on peak flows, stormflows, and annual runoff of three Northeastern watersheds; and we compare peak flows, percentage of runoff, high- and low-flow intervals, and hydrologic responses between four partially urbanized and nine mostly forested watersheds.

Urbanization—the swelling of cities, the sprawling of suburbs, and the blossoming of beltways—is the most revealing effect of our continuing population explosion. In the third century, Rome occupied an area of slightly more than 5 square miles; now it occupies 580 square miles. In the fourteenth century, London covered slightly more than 1 square mile; now it covers about 700 square miles. And metropolitan New York, which had only scattered settlements 300 years ago, now covers more than 2,500 square miles *(Mumford 1956)*.

The 12 States of the Northeast are the most densely populated in the United States: their 251 people per square mile far exceed the 128 in the Lake States, the 99 in California, and the 73 in the Southeast. And cities in the Northeast are beginning to coalesce: three-fourths of the population live in one-fourth of the region, the Megalopolis that stretches 500 miles from Washington to Boston and includes Baltimore, Philadelphia, and New York (fig. 1). In this area the population density has increased to 700 people per square mile.

Most of the population outside Megalopolis is also urbanized —in nine metropolitan areas, of which the largest are Pittsburgh-Johnstown-Altoona, Syracuse-Utica-Rome, and Albany-Schenectady-Troy. Twenty-one percent of the land area of the Northeast is classified by the U. S. Bureau of Census as standard metropolitan statistical areas with populations of more than 100,000. Metropolitan areas range from 0 to 61 percent of total state area:

| | *Percent* | | *Percent* |
|---|---|---|---|
| Vermont | 0.0 | New York | 26 |
| New Hampshire | .1 | Massachusetts | 32 |
| Maine | .2 | Connecticut | 35 |
| West Virginia | 9.4 | Pennsylvania | 35 |
| Delaware | 19 | New Jersey | 52 |
| Maryland | 25 | Rhode Island | 61 |

As the cities have grown, they have spread over farm and forest. Between 1942 and 1956, about 230,000 acres of cultivable land in New England and 1,150,000 acres in the Middle Atlantic States were converted to nonagricultural uses. An estimated 238 acres of fields and trees have been engulfed for each increase of 1,000 in urban population *(Bogue, 1956)*.

Most of this land was converted to residential areas, roads, and public-use areas. Mean proportions of areas devoted to various uses in 14 large Northeastern cities were calculated from Niedercorn and Hearle's *(1963)* data, as follows:

| | *Percent* |
|---|---|
| Residential | 28 |
| Road and highway | 25 |
| Other public | 20 |
| Vacant | 12 |
| Industrial | 11 |
| Commercial | 4 |

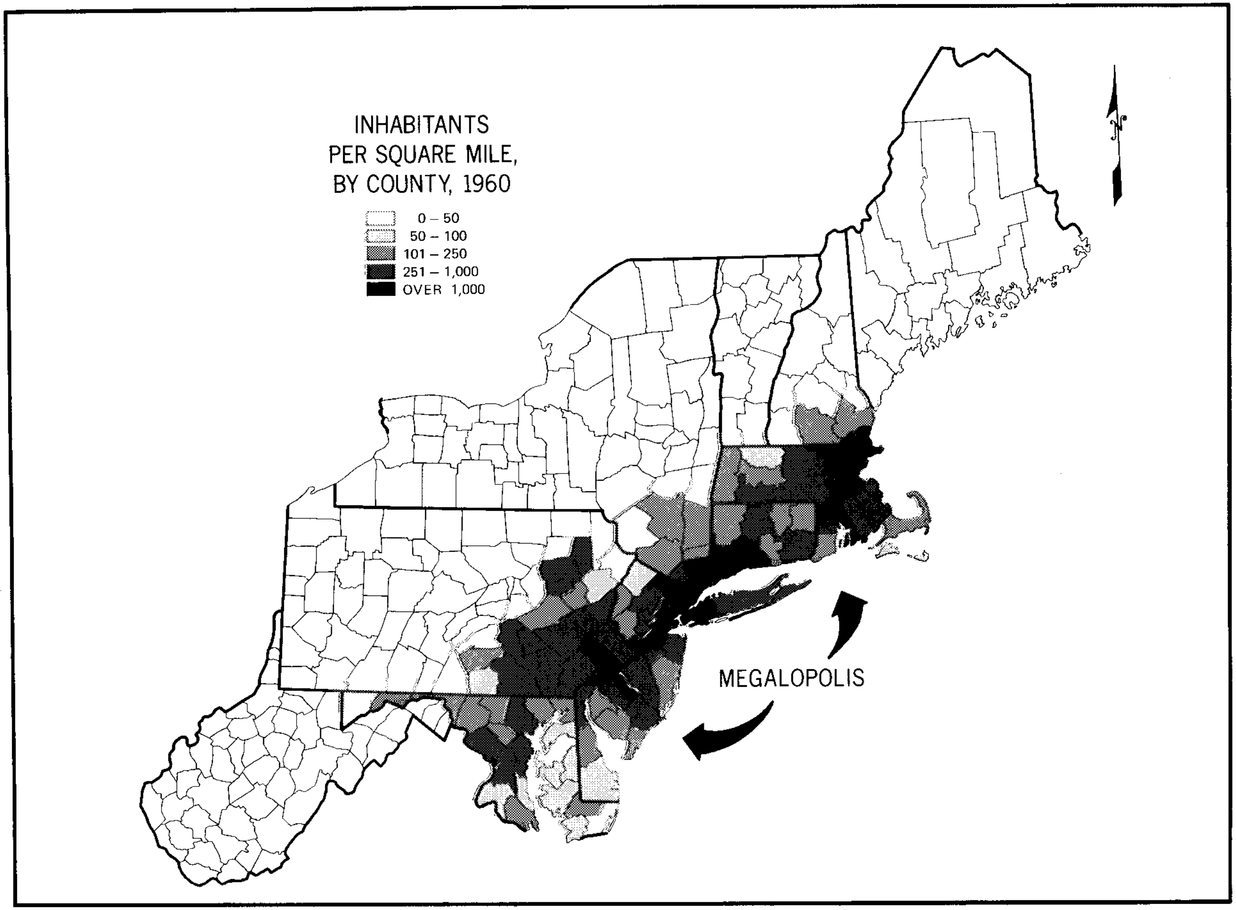


Figure 1.—The Megalopolis of the Northeast.

Conversion of farm and forest to residential areas, roads, parking lots, lawns, and other urban uses obviously should have major effects on the hydrology of the area—specifically, on the distribution of precipitation to evapotranspiration, to soil-moisture storage, and to runoff. The degree of influence will depend on the degree of urbanization, expressed most simply as the proportion of the area covered with an impervious surface. This can range from almost 100 percent in commercial districts to a small percentage in suburban areas. Antoine *(1964)* gave these percentages of impervious area for various urban land uses:

| | *Percent* |
|---|---|
| Cemeteries | 5 |
| Parks and recreation | 15 |
| Residential lot area: | |
| 15,000 square feet | 25 |
| 6,000 to 14,999 square feet | 40 |
| 5,999 square feet | 80 |
| Semipublic and public | 75 |
| Industrial | 90 |
| Commercial | 100 |

In other estimates, impervious areas were found to occupy 30, 50, and 72 percent of three city blocks in St. Louis *(Horner and Flynt 1936)*, and impervious areas were estimated to cover about 50 percent of Brooklyn *(Thomas 1956)*.

Suburbs have smaller proportions of impervious areas than city areas. For instance, the mean proportions of areas occupied by rooftops, pavement, and lawn in Philadelphia suburbs were estimated by Felton and Lull *(1963)*:

| *Size of lot (acres)* | *Rooftops (percent)* | *Pavement (percent)* | *Lawns (percent)* |
|---|---|---|---|
| 1.8 | 2 | 6 | 92 |
| .5 | 6 | 11 | 83 |
| .4 | 8 | 18 | 74 |
| .2 | 12 | 20 | 68 |

Proportionately, rooftops and pavements occupied four times as much area in the smallest lot as in the largest. Carter *(1961)* found the percentage of impervious surface area in suburban Washington, D. C., to be about 12 percent. Probably the largest paved areas in the suburbs, exclusive of streets, are the modern shopping centers, which require three to four times as much space for car parking as for merchandising floor area.

What has happened to the hydrology of the areas on which houses, lawns, streets, and commercial and industrial areas have replaced farm and forest? One way to find out is to compare urban hydrology to forest hydrology, using a protected forest as the base condition or control. That is what we have done. Results from research in forest hydrology conducted during the past 40 years and in urban hydrology conducted, for the most part, over the past 20 years were used to facilitate this comparison.

## HYDROLOGIC PROCESSES

The hydrologic processes that we consider briefly below are interception, infiltration and overland flow, soil-moisture storage, evapotranspiration, runoff, and peak flows.

### Interception

Hardwood and conifer canopies in the Northeast intercept and evaporate about 15 to 20 percent of the growing-season rainfall before it reaches the forest floor. In winter, hardwoods intercept about 7 percent of the precipitation and conifers about 18 to 25 percent, depending upon how much precipitation occurs as snow. For example, of an average annual precipitation of 45 inches in central Massachusetts, hardwoods intercept about 5 inches and conifers about 9 inches, respectively 11 and 20 percent of the annual precipitation *(Lull 1967)*.

City streets can intercept and store on their surfaces perhaps 0.04 to 0.10 inch of water *(Viessman 1966)*. The amount of precipitation intercepted by roofs and sides of urban buildings, and evaporated from them, has probably never been estimated; but it is very likely less than 0.04 inch. In light of the great variety of construction that protrudes from city surfaces, any estimates would be highly speculative. For example, a city block of 1 acre occupied by a 10-story building would have about 2 acres in sidewalls, which would give an interception surface-area to ground-area ratio (including roof) of 3:1. In comparison, leaf areas, (both sides) of forest canopies have ratios that range from 2:1 to 9:1

*(Kittredge 1948).* If the sidewalls (only partially wetted) could intercept 0.01 inch of rainfall and the roof 0.04 inch, and if 120 rainfalls occurred during a year amounting to 45 inches precipitation, 16 percent would be intercepted—about the percentage intercepted by trees in summer.

Residential areas, where the principal intercepting areas are lawns, would intercept somewhat less. From measurements of grass interception by Burgy and Pomeroy *(1958),* we estimate a lawn 2 inches high could intercept about 0.01 inch of water. And if we add to this an estimated depression storage of 0.04 inch for the entire area, the total residential-area interception would be about 0.05 inch or, in relation to the 45-inch annual rainfall noted above, a total annual interception of about 13 percent.

## Infiltration and Overland Flow

Infiltration in the undisturbed forest is generally assumed to be at rates greater than rainfall intensities. Undisturbed litter and humus and underlying soil beneath the forest canopy are immediate evidence that overland flow has not occurred. However, on disturbed areas such as logging roads and skid trails where soil has been compacted, evidence of overland flow is common; and infiltration in such areas obviously is often at rates lower than rainfall intensities. In general, these areas constitute 10 to 20 percent of the area logged.

In urban areas, infiltration can range from zero for paved areas and roofs to rates exceeding rainfall intensities in those uncommon, soil-covered areas not subject to traffic by vehicles or people. Lawns have surprisingly low infiltration capacities because their soils have often been man-mixed, bulldozed into position, and compacted by frequent mowing and trampling. In one study, ring-infiltrometer tests showed that an average of 0.10 inch of water infiltrated per minute into lawns and 0.58 inch into forest soil *(Felton and Lull 1963).*

As noted above, overland flow is generally absent in the undisturbed forest. On urban areas that are completely paved or roofed, overland flow from any rainfall will equal rainfall less surface retention (the volume required to wet all surfaces, depression storage, and evaporation during rainfall). Annually, the runoff might constitute 85 percent of the precipitation. This has been confirmed by several reports on small watersheds that were paved or sprayed with asphalt to collect the precipitation for water supply *(Chinn 1965; Myers and others 1967).*

In other areas runoff will depend on the proportion of the surface that is impervious. For instance, Horner and Flynt *(1936)* found that for small urban areas in St. Louis the average ratio of runoff rates to rainfall rates was 0.4 for an area that was 30 percent impervious, 0.65 for a 50-percent impervious area, and 0.8 for a 72-percent impervious area. Under high-intensity rainfall, lawns can produce considerable overland flow. Horner and Flynt *(1936)* also found that sprinkling sodded plots at the rate of 2.5 inches per hour resulted in runoff rates of 1.60 and 2.00 inches per hour 30 to 40 minutes after overland flow began.

### Soil-Moisture Storage

In the Northeast, most of the forest is limited to hilly and mountainous areas typified by fairly coarse-texture soils that range from 2 to 5 feet in depth. Starting from a dry state, these soils could retain 4 to 10 inches of water. Their storage potential, particularly during the frequent dry periods in summer, is such that very little summer precipitation reaches streamflow or the groundwater table.

In urban areas, storage is considerably less, ranging from 0.04 inch of depression storage on paved areas to greater amounts in lawns and parks. Brater *(1968)* calculated interception and storage of 0.2 inch for permeable portions of three drainage basins in the Detroit metropolitan area. Hicks *(1944)* found in Los Angeles that about 10 percent of the average rainfall was lost to storage, and portions of this went into sewer manholes and basements.

### Evapotranspiration

Annual forest evapotranspiration in the Northeast ranges from about 23 inches in New England to 29 inches in the Coastal Plain of Delaware and Maryland *(Lull 1968)*. Evapotranspiration is at a maximum for forest areas because of their complete occupancy of an area, and their low albedo, deep roots, and interception.

On impervious urban areas that receive an annual rainfall of 40 to 50 inches, evaporation can range from 4 to 5 inches a year or on an estimated 10-percent storage of annual rainfall, based on estimated depression storage and number of rainfalls.

In residential areas, summer runoff from roofs and sidewalks that infiltrates into lawns can add to the water available for evapotranspiration. Water used for sprinkling lawns and gardens can also greatly increase it. For instance, in Pasadena, California, Gleason *(1952)* estimated annual evapotranspiration for impervious areas to be about 4 inches of water; for residential areas, 24 inches; and for areas of lawns and trees, 36 inches or more. Annual precipitation was about 20 inches in this area.

**Runoff**

Runoff from forested watersheds in the Northeast ranges from about 24 inches in mountainous New England to about 15 inches in the southern part of the region. Compared with urban runoff, forest runoff is reduced by greater interception, higher infiltration, less overland flow, greater soil-moisture storage, and higher evapotranspiration. Two studies have shown that the conversion of forest land to urban use increases the amount of precipitation that appears as runoff. Urbanization of a small forested watershed near Seattle, Washington, increased the proportion of rainfall that appeared as daily discharge about three times: from 0.099 to 0.296 c.f.s. per inch of rainfall *(Wooldridge 1967)*. And in an East African study, runoff from the largest storms on a 31-acre forested area amounted to less than 1 percent of the rainfall as contrasted with runoff from a 32-acre housing and administrative area, where runoff was 36 percent of rainfall *(Dagg and Pratt 1962)*.

Rough estimates of the distribution of annual rainfall in a Northeastern hardwood forest, and in Northeastern urban areas with 50- and 10-percent impervious covers, were as follows:

| | Forest (inches) | 50-percent impervious (inches) | 100-percent impervious (inches) |
|---|---|---|---|
| Precipitation | 40 | 40 | 40 |
| Interception | 5 | 3 | 2 |
| Overland flow | (0) | (18) | (36) |
| Soil-moisture storage | (6) | (3) | (2) |
| Evapotranspiration | 15 | 12 | 2 |
| Runoff | 20 | 25 | 36 |

Values in parentheses indicate temporary storage: soil-moisture in storage would presumably be evapotranspired and overland flow would become runoff. In the 50-percent impervious area, 18 inches were estimated as overland flow, of which one-fourth, 4.5 inches, were assigned to growing-season evapotranspiration from pervious areas; this amount, plus 7.5 inches of evapotranspiration from the pervious area, accounts for the total of 12 inches.

The effect of urbanization on runoff would also depend on precipitation and evapotranspiration of the area. Where evapotranspiration is greater than in the Northeast, runoff would be less but the percentage change in runoff due to urbanization would be greater. Variable results might be expected. James (1965) estimated from a California streamflow record that over a 10-year period the runoff volume from a completely urbanized watershed was 2.29 times the volume from the same watershed when it was in a rural condition.[1] In Austin, Texas, runoff increased 1.9, 2.1, and 2.4 times for watersheds with 21-, 27-, and 38-percent impervious cover *(Espey and others 1965)*, respectively.

## Peak Flows

Peak flows from undisturbed forest watersheds are minimized by high-infiltration capacities and absence of overland flow. However, under wet conditions, high rates of runoff can be produced from subsurface flow.

Studies of increases in peak flows with progressive urbanization, or comparisons of peak flows from small urban and rural water-

[1] The term "rural" designates an open-land nonforest condition in this study, and also in the Mississippi study *(Wilson 1967)* and the Texas study *(Van Sickle 1962-63)*. Pre-urbanization land use for the other studies referred to in this respect was not given.

sheds, suggest that urbanization increases peak flows by 1.2 to 5 times. As examples, suburban developments in Washington, D. C., which increase the impervious area by 12 percent, can increase flood peaks by 1.8 times *(Carter 1961)*. In Long Island, peak discharges with an occurrence interval of 1.15 years increased 2.3 times during a 21-year period of progressive urbanization *(Sawyer 1961)*. In New Jersey, Potter *(1957)* found that the actual maximum annual peak for a 10-year recurrence interval was 1.5 times greater than the peak derived from a regional prediction procedure based on watershed areas and a rainfall index. At Jackson, Mississippi, mean maximum annual flood peaks for a totally urbanized basin were about 4.5 times those for a similar but rural stream *(Wilson 1967)*.

A model analysis of a California streamflow record has shown that urbanization increased flood peaks an estimated 1.6 to 2.3 times *(James 1965)*. And studies in Texas and Michigan *(Van Sickle 1962-3; Espey and others 1965)* indicate flood peaks from urban watersheds were two to five times greater than those from rural watersheds. According to Waananen *(1961)*, peak runoff from developed areas in northern New Jersey, Michigan, Pennsylvania, and Virginia averages three to four times greater than that from upstream or adjacent natural areas. Urbanization of a watershed in the northern part of Tokyo in 1958-66 increased flood peaks by a factor of three *(Kinosita and Sonda 1967)*.

Design peak runoff rates calculated by the rational method for urban and forest conditions give somewhat greater ratios. Peaks from urban areas 30-percent impervious were estimated to be four times greater than peaks from flat areas of woodland on open sandy loam; for 50-percent impervious areas they were 5.5 times greater; and for 70-percent impervious areas they were 6.5 times greater *(Schwab and others 1957)*.

Leopold *(1968)* synthesized data from several studies to show the increase in the average annual flood for degrees of urbanization, defined by increases in percentage of areas sewered and made impervious:

| *Percentage of area sewered* | *Percentage of area impervious* | *Ratio to average annual flood* |
|---|---|---|
| 0 | 0 | 1 |
| 20 | 20 | 1.5 |
| 40 | 40 | 2.3 |
| 50 | 50 | 2.7 |
| 80 | 60 | 4.2 |
| 100 | 60 | 4.4 |

Comparison of peak flows from the Dagg and Pratt *(1962)* East African study in which discharges from a forested watershed and an urbanized area were measured, show even greater differences. From 31 storms the ranges of peak flows were:

| *Forested area* | | *Housing nad administrative area* | |
|---|---|---|---|
| *Storms (No.)* | *Peak flow (c.s.m.)* | *Storms (No.)* | *Peak flow (c.s.m.)* |
| 18 | 0.01 to 0.1 | 2 | 1.0 to 10 |
| 11 | 0.1 to 1.0 | 10 | 10 to 100 |
| 2 | 1.0 to 10 | 18 | 100 to 1,000 |
| — | — — | 1 | 1,000 to 10,000 |

## Water Quality

Stages in the transition of forest and farm land to urban areas and the hydrologic effects of these changes have been described by Savini and Kammerer *(1961)*. The resultant marked increases in sedimentation have been most strikingly demonstrated by studies in the vicinity of Washington, D. C., and Baltimore, Md., where land clearing for suburban construction has produced record sedimentation rates. After a review of these studies, O'Bryan and McAvoy *(1966)* concluded that sediment yields that can be expected from the 350-square mile Gunpowder Falls basin, under various land uses were as follows:

| | *Sediment (tons per square mile per year)* |
|---|---|
| Forest land | About 50 |
| Urban and suburban land | 50 to 100 |
| Farmland | 1,000 to 5,000 |
| Land stripped for construction | 25,000 to 50,000 |

For an average annual runoff of 15 inches, the maximum turbidities for the above sediment yields, in parts per million, are 45, 90, 4,500, and 45,000. Recommended maximum turbidity for drinking water is 5 p.p.m.

The above estimate of 50 tons per square mile per year or 45 p.p.m. may be high for sedimentation from a protected forest watershed. Streamflow from a protected forest is generally prized for its purity, and its turbidity rate may generally be well below the drinking-water standard. For instance, streamflow from second-growth forested watersheds at the Fernow Experimental Forest in West Virginia had an average turbidity under 5 p.p.m. *(Reinhart and others 1963)*, equivalent to 9 tons of sediment or less per square mile per year. In Kentucky, sediment yield from a small heavily forested watershed was 15 tons per square mile per year *(Wolman and Schick 1967)*.

In New Jersey, Anderson and McCall *(1966)* found that suspended-sediment varied with topography and land use. Forest flatland had yields of 10 to 40 tons per square mile annually; moderately heavily urbanized areas on flatland, 25 to 100 tons; forest upland, 25 to 100 tons; and heavily urbanized upland, 75 to 500 tons.

For a representative selection of rural watersheds in Maryland, Wolman and Schick *(1967)* showed a range in sediment yield of 200 to 900 tons per square mile per year as compared with a yield of 1,000 to 140,000 tons per square mile per year from areas undergoing construction around Washington, D. C., and Baltimore.

Urban areas under construction can thus become bountiful sources of sediment, especially where modern earth-moving equipment reshapes soil into building lots that remain unprotected. According to Holeman and Geiger *(1959)*, such areas may remain bare for about 3 months for a single dwelling construction; and large housing and apartment developments may expose soil more than a year. An analysis of building permits issued in Baltimore County showed that 40 percent of the sites were open for more than 9 months, and 25 percent were open for more than 1 year *(Wolman and Schick 1967)*.

A notorious example of erosion is the Lake Barcroft area near Washington, D. C., where 25,000 tons of sediment have been deposited for each square mile of residential construction *(Guy and Ferguson 1962)*. In another housing project in the same area, Guy *(1963)* estimated that the sediment load for the construction period was equivalent to 121,000 tons per square mile—equivalent to removal of about 1.2 inches of soil. In metropolitan Baltimore County, Wolman and Schick *(1967)* estimated that about 1,800 tons of sediment were produced per 1,000 increase in population, and for Prince Georges County, near Washington, a yield of 700 tons per 1,000 increase.

As noted earlier, once construction is completed, sedimentation rate of urban and suburban areas may drop to 50 to 100 tons per square mile, but this is still 5 to 10 times the rate from protected forested watersheds such as at the Fernow Experimental Forest in West Virginia.

Careless logging practices can also quickly produce turbid flow and substantial quantities of sediment. For instance, over a period of 1 year at the Fernow Experimental Forest, careless logging produced an average turbidity of 490 p.p.m., or 862 tons of sediment per square mile, and an instantaneous peak turbidity of 56,000 p.p.m. Without remedial measures, the average turbidity dropped to 38 p.p.m. the first year after logging and to 1 p.p.m. the second year after logging. This rapid self-healing, perhaps characteristic of stony forest soils in the Northeast, was due to the development of an erosion pavement and the invasion of vegetation on the logging roads.

## URBANIZATION EFFECTS ON SMALL FORESTED WATERSHEDS

As the foregoing discussion of hydrologic processes indicates, urbanizing a forested watershed will reduce evapotranspiration, increase runoff, and increase peak flows. Other things being equal, the magnitude of these effects will depend on the degree of urbanization, or, at its simplest, the proportion of the watershed that is rendered impervious. To demonstrate these effects, streamflow and climatic records of a small forested watershed were utilized.

Streamflow and climatic records from the Dilldown Watershed in Pennsylvania *(McQuilkin and others 1956)* were used to estimate evapotranspiration and runoff effects. This 1,529-acre experimental watershed possessed a forest cover largely of scrub oak. Water-year 1953 was selected as being representative of the 10 years of published records. We computed daily potential evapotranspiration by the Hamon procedure *(Hamon 1963);* and we estimated runoff from the daily record of precipitation and an estimated soil-moisture content with a total 6-inch storage.

Precipitation for the water-year measured 58.06 inches and runoff 36.50 inches; and their difference, estimated evapotranspiration, was 21.56 inches. Estimated potential evapotranspiration from a daily water balance was somewhat greater, 26.0 inches; and estimated runoff was somewhat less, 35.0 inches. But there was sufficient similarity to justify using these procedures to illustrate the effects of three degrees of urbanization.

Daily water balances were computed, simulating a watershed that was 25-, 50-, and 75-percent impervious. On the impervious area, a depression storage of 0.04 inch for each daily rainfall was assumed evaporated; except for this, potential evapotranspiration was assumed to be zero. Runoff from the paved surfaces was assumed to empty directly from conduits into streamflow.

Estimated annual and seasonal potential evapotranspiration and runoff from forested and impervious areas are given in table 1.

Annual potential evapotranspiration was reduced 19, 38, and 59 percent by 25-, 50-, and 75-percent impervious cover, respectively. In each of the four examples (including the 100-percent forested area), about three-fourths of the potential evapotranspiration occurred during the 6-month growing season (April through September). Almost equal evapotranspiration from the impervious area, by season, reflects similarity in number of days of precipitation: 71 during the growing season and 75 in the dormant season.

Annual runoff increased by 15, 29, and 41 percent with increases of impervious area. In the completely forested area, 80 percent of the runoff occurred during the dormant season. In the urbanized area the distribution was more uniform: with a 75-percent im-

Table 1.—*Estimated potential evapotranspiration and runoff (annually and seasonally), in inches*

| Period | 100-percent forest | 75-percent forest | 25-percent impervious | 50-percent forest | 50-percent impervious | 25-percent forest | 75-percent impervious |
|---|---|---|---|---|---|---|---|
| | | | POTENTIAL EVAPOTRANSPIRATION | | | | |
| Annual | 26.0 | 19.6 | 1.4 | 13.0 | 2.9 | 6.2 | 4.3 |
| Growing season | 20.1 | 15.1 | .7 | 10.0 | 1.4 | 5.0 | 2.1 |
| Dormant season | 5.9 | 4.5 | .7 | 3.0 | 1.5 | 1.2 | 2.2 |
| Total annual | 26.0 | 21.0 | | 15.9 | | 10.5 | |
| | | | RUNOFF | | | | |
| Annual | 35.0 | 26.2 | 14.1 | 17.5 | 27.6 | 8.8 | 40.5 |
| Growing season | 7.0 | 5.2 | 5.9 | 3.5 | 11.5 | 1.8 | 16.9 |
| Dormant season | 28.0 | 21.0 | 8.2 | 14.0 | 16.1 | 7.0 | 23.6 |
| Total annual | 35.0 | 40.3 | | 45.1 | | 49.3 | |

pervious cover, 62 percent of the runoff occurred in the dormant season.

In a similar comparison for the South Branch of the Raritan River in New Jersey, Muller *(1968)* estimated an evapotranspiration of 23.0 inches and a runoff of 24.0 inches for the basin in its rural condition. And he estimated that if one-half of the basin were rendered impervious by urban surfaces, evapotranspiration would be reduced to 11.5 inches and runoff increased to 35.5 inches, changes proportionate to those estimated for the Dilldown Watershed (table 1). Here again the estimated increases occurred mostly during the summer months.

## URBANIZATION EFFECTS ON STREAMFLOW RECORDS

After studying the effects of urbanization on individual hydrologic processes and calculating their effects on runoff, we wondered if the influence of urbanization on streamflow could be detected by analyses of actual surface water records. We tried two approaches. The first involved three watersheds that were increasingly urbanized during the past 24 to 35 years. In this analysis, maximum annual peak flows, annual ratios of stormflow to precipitation (hydrologic response), and deviations of actual runoff from predicted runoff were plotted and examined for trends. The second method involved comparisons of various parameters of streamflow for four partially urbanized watersheds and nine mostly forested watersheds, calculated for the period 1940 to 1957. All watersheds studied were less than 100 square miles in area.

### Progressive Urbanization

Annual maximum peak flows, annual hydrologic responses, and annual runoff deviations are shown in figure 2, and their regression trends are given in table 2. Annual maximum peak flows are the momentary peaks. Hydrologic responses are the ratios of annual stormflow to annual precipitation, calculated according to the procedures described by Hewlett *(1967)*. Runoff deviations

Table 2.—*Trends in peak flows, hydrologic responses, and annual runoff deviations on progressively urbanized watersheds.*

| Watershed | Period | Area | Urban area[1] | Regression trends (slope coefficients) | | |
|---|---|---|---|---|---|---|
| | | | | Peak flows | Hydrologic response | Annual runoff deviations |
| | | *Square miles* | *Per-cent* | *C.f.s. per year* | *Stormflow per precipitation per year* | *Inches per year* |
| Weasel Brook, N. J. | 1938-62 | 4.45 | 98 | 10** | [2] 0.0063** | [2]0.93** |
| Second River, N. J. | 1938-64 | 11.6 | 98 | 4 | .0019* | .18 |
| Rock Creek, Md. | 1930-65 | 62.2 | 25 | 17 | .008* | .07 |

[1] From U.S. Geol. Surv. topographic quads 1955 for Weasel Brook and Second River, and 1956 for Rock Creek.
[2] For 1948-62.
**Regression slope significantly different from zero at 1-percent level.
* Regression slope significantly different from zero at 5-percent level.

**Figure 2.—Peak flow, hydrologic response, and annual runoff deviations of progressively urbanized watersheds, and their trends.**

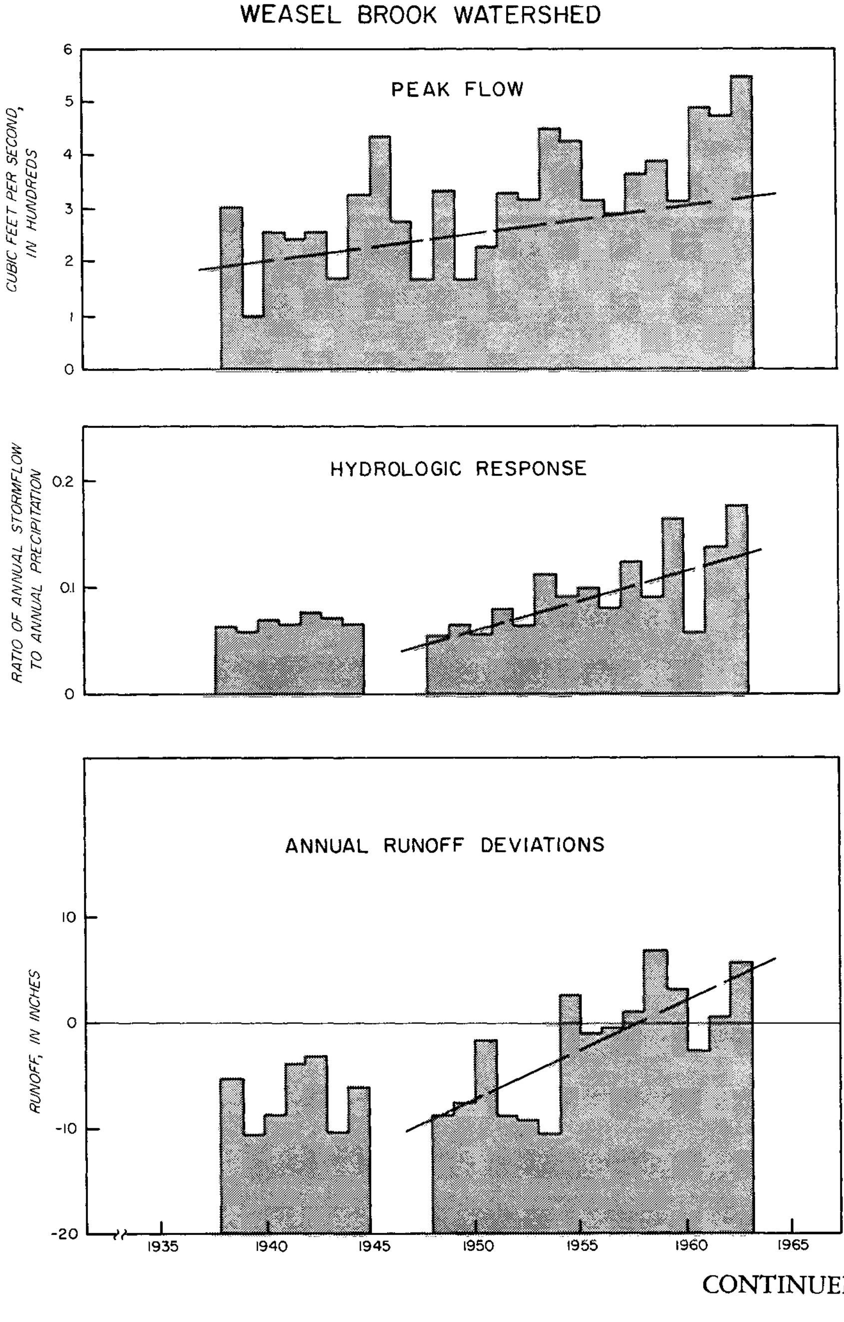


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**Figure 2.—Continued**

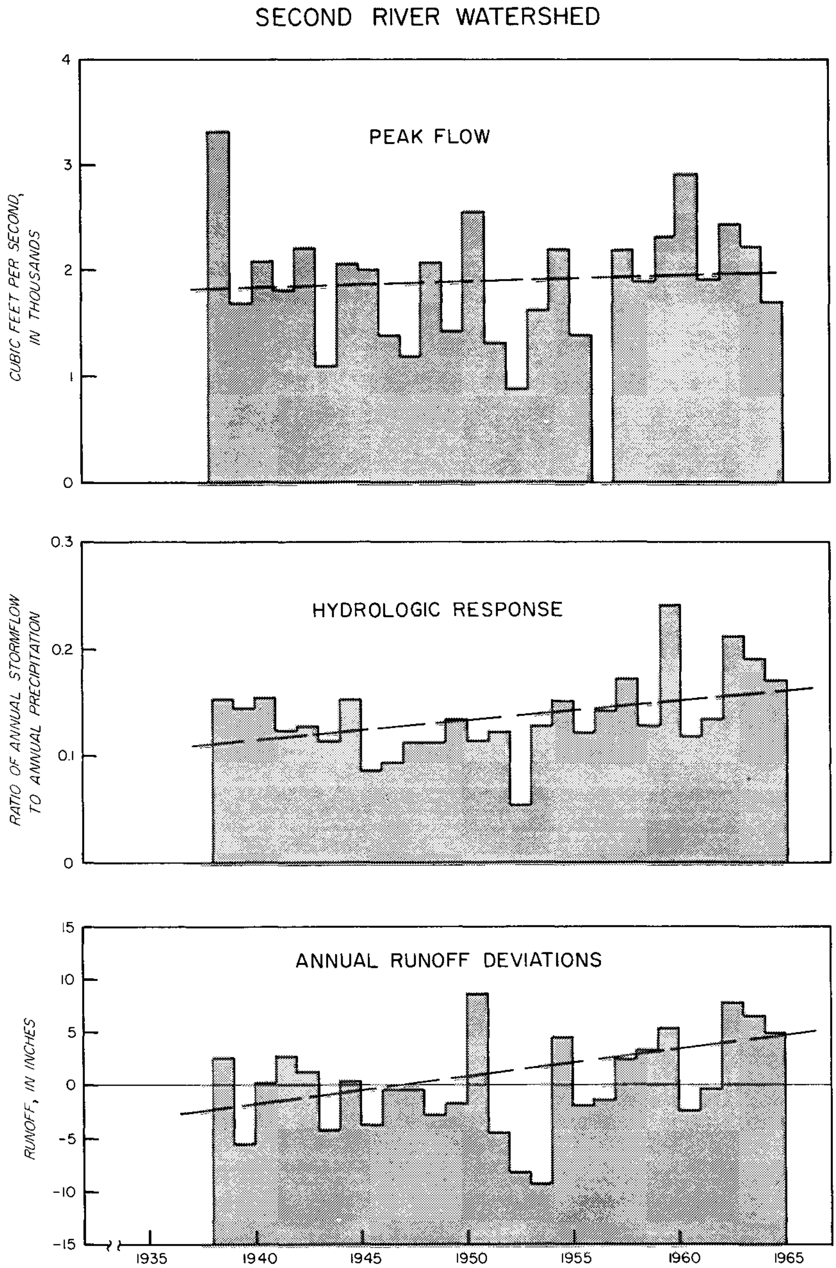


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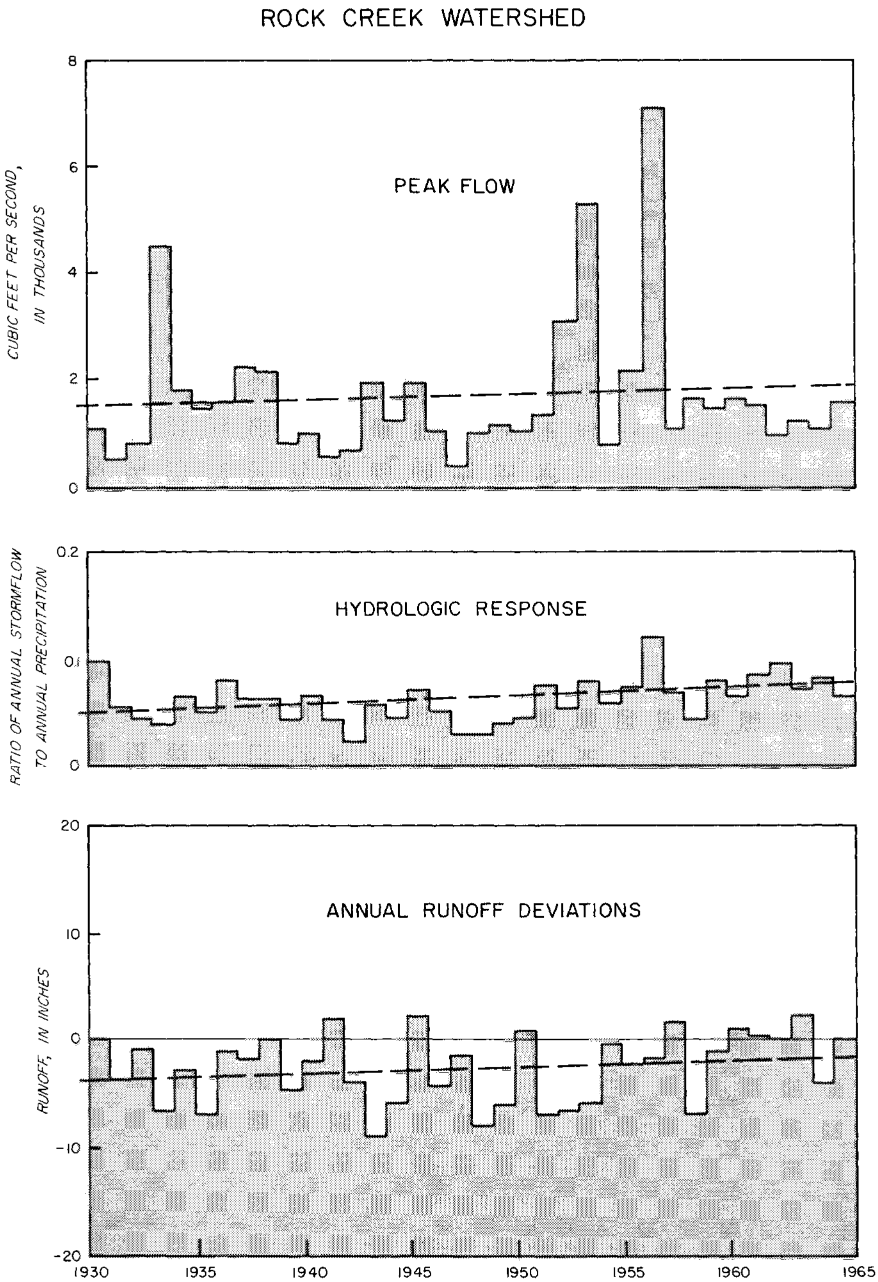
**Figure 2.—Continued**



are the differences between actual annual runoff and predicted annual runoff, the latter obtained from a computer program devised by Black *(1967)* for the Thornthwaite and Mather *(1957)* method for computing the annual water balance.

All nine linear regressions indicated increasing peak flow, stormflow, and annual runoff during the periods of increasing urbanization; five of the regressions had slopes statistically significantly different from zero. Weasel Brook, the smallest watershed, showed the greatest reaction: peak flows increased about 2 c.s.m. per year during the 25-year period and annual runoff increased almost 1 inch per year during the 15-year period. Annual ratios of stormflow to precipitation appeared to be the most sensitive indicator of urbanization.

### Partially Urban vs. Forested Watersheds

This comparison was limited to the southern New England region. We used two approaches. In the first approach, for 1940-57, mean maximum annual momentary discharge and mean maximum annual daily discharge over 10 c.s.m., and the number of such discharges, were calculated for six watersheds where high flows were not regulated. In the second approach, streamflow parameters other than maximum discharges were analyzed; this involved analyses of records from the same six watersheds plus records from seven watersheds where flow was regulated to some degree by power plants and reservoirs. Locations of the 13 watersheds are shown in figure 3.

The analyses involved calculations of: (1) the percentage of annual and summer (June-August) precipitation that appeared as runoff; (2) the shortest number of consecutive days required to produce 50- and 25-percent annual discharge (high-flow intervals), and the greatest number of consecutive days to produce 1- and 5-percent annual discharge (low-flow intervals), using Satterlund and Eschner's *(1965)* procedure; and (3) the hydrologic responses for the 1957-59 period. Results are given in tables 3 and 4.

Table 3.—*Mean maximum annual momentary peak flows and mean annual daily discharges over 10 c.s.m., 1940-57*

| Watershed | Area | Land use | | | Mean annual momentary peak | Daily discharge over 10 c.s.m. | |
|---|---|---|---|---|---|---|---|
| | | Forest | Open | Urban | | No. | Mean |
| | *Square miles* | *Pct.* | *Pct.* | *Pct.* | *C.s.m.* | *Days* | *C.s.m.* |
| | | URBAN | | | | | |
| Second River, N. J. | 11.6 | 2 | — | 98 | 136 | 6 | 16 |
| Saddle River, N. J. | 54.6 | 34 | 32 | 33 | 25 | 4 | 15 |
| | | FORESTED | | | | | |
| Middle Branch Westfield River, Mass. | 52.6 | 93 | 7 | — | 89 | 8 | 19 |
| West Branch Westfield River, Mass. | 93.7 | 94 | 6 | — | 70 | 8 | 19 |
| Naugatuck River, Conn. | 71.9 | 77 | 19 | 4 | 83 | 9 | 16 |
| Leadmine Brook, Conn. | 24.0 | 86 | 14 | — | 81 | 9 | 17 |

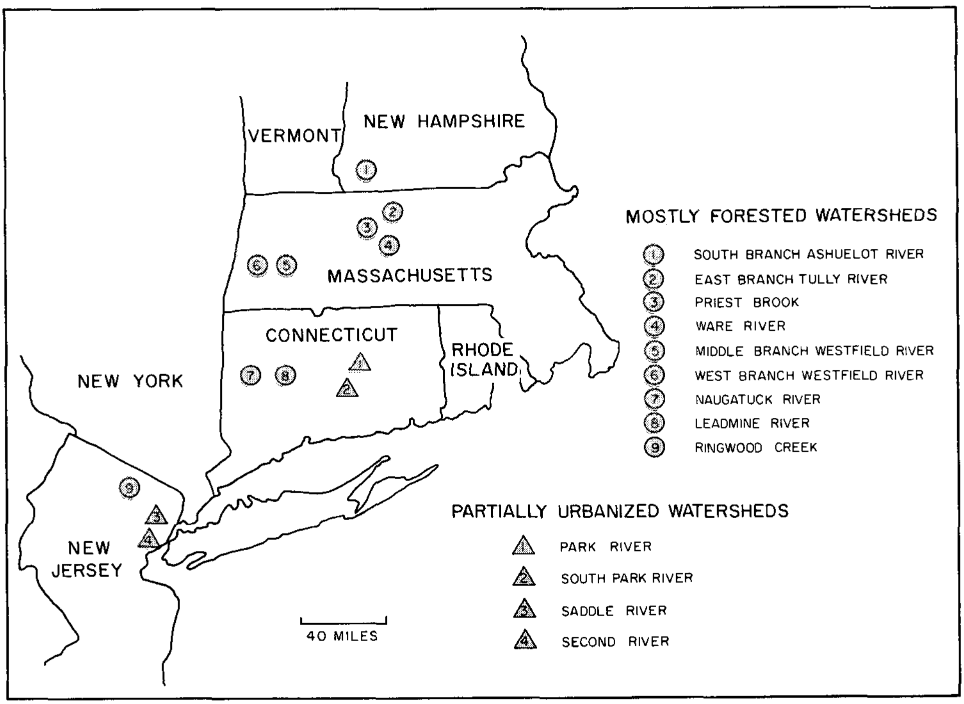
Table 4.—*Percent runoff, flow intervals, and hydrologic responses, 1940-57*

| Watershed | Area | Land use | | | Percent of precipitation to runoff | | High-flow interval | | Low-flow interval | | Hydrologic response |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Forest | Open | Urban | Annual | Summer | 25% | 50% | 1% | 5% | |
| | *Square miles* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Days* | *Days* | *Days* | *Days* | *Ratio* |
| | | | | | URBAN | | | | | | |
| Second River, N. J. | 11.6 | 2 | — | 98 | 45 | 44 | 51 | 140 | 13 | 40 | 0.187 |
| Park River, Conn. | 74.0 | 38 | 31 | 27 | 51 | 29 | 34 | 102 | 18 | 62 | .104 |
| South Branch Park River, Conn. | 40.6 | 48 | 13 | 34 | 55 | 33 | 40 | 112 | 14 | 51 | .106 |
| Saddle River, N. J. | 54.6 | 34 | 32 | 33 | 55 | 36 | 46 | 120 | 16 | 53 | .078 |
| Mean | — | — | — | — | 52 | 36 | 43 | 118 | 15 | 52 | 0.119 |
| | | | | | FORESTED | | | | | | |
| Ware River, Mass. | 96.8 | 90 | 8 | — | 57 | 23 | 33 | 90 | 34 | 79 | 0.061 |
| South Branch Asheulot River, N. H. | 36.0 | 91 | 8 | — | 50 | 14 | 25 | 76 | 36 | 72 | .085 |
| Priest Brook, Mass. | 19.4 | 91 | 8 | — | 57 | 16 | 26 | 81 | 38 | 80 | .042 |
| East Branch Tully River, Mass. | 50.4 | 92 | 7 | — | 48 | 16 | 28 | 79 | 44 | 82 | .053 |
| Middle Branch Westfield River, Mass. | 52.6 | 93 | 7 | — | 53 | 17 | 24 | 79 | 42 | 93 | .096 |
| West Branch Westfield River, Mass. | 93.7 | 94 | 6 | — | 55 | 14 | 26 | 81 | 40 | 89 | .101 |
| Ringwood Creek, N. J. | 19.1 | 93 | 3 | — | 53 | 23 | 30 | 96 | 46 | 86 | .057 |
| Naugatuck River, Conn. | 71.9 | 77 | 19 | 4 | 61 | 32 | 30 | 89 | 22 | 78 | .100 |
| Leadmine Brook, Conn. | 24.0 | 86 | 14 | — | 60 | 26 | 29 | 89 | 51 | 92 | .098 |
| Mean | — | — | — | — | 55 | 20 | 28 | 84 | 29 | 83 | 0.077 |

Peak discharges from the urban watersheds bracket the peak flows from the forested ones, table 3. Maximum mean daily discharges and their mean number per year are greater from the forested watersheds.

Urbanization may not necessarily result in increased peak discharges from a watershed because these events are influenced not only by the areal extent of urbanization but also by the location of the urbanized area in respect to the entire basin. For example, the urbanized area of Saddle River in New Jersey is concentrated at the lower end of the basin. Peak flows from this area probably run off much more rapidly than before urbanization. Consequently, even though the peak discharges from these small down-basin urbanized areas may be higher than before, they are discharged from the basin more rapidly; and they are at a lower stage of regression before the main peak from the larger, slower-draining,

**Figure 3.—Location of partially urbanized and mostly forested watersheds.**



non-urbanized upper basin reaches the lower end. Hence the net result of urbanizing the lower end of a basin can result in a dispersion of desynchronization of storm peaks from the urban and non-urban areas, and a general reduction in size of the momentary peaks from the entire basin.[2]

For parameters other than maximum discharges, the percentage of summer precipitation that appears as runoff is considerably greater in the urban watersheds than on the forested watershed, (table 4). It took, on the average, 15 and 34 days longer to discharge 25 and 50 percent of the annual runoff from the urban watersheds than from the forested watersheds—or, put another way, the high flows were lower. Conversely, low flows during the growing season were higher, requiring fewer days to discharge 1 and 5 percent of the annual flow. The higher concentration of flow and the distinct difference in streamflow timing between forested and partially urbanized watersheds are further illustrated in figure 4. Finally, about 12 percent of the precipitation appears as stormflow from urban areas and about 8 percent from forested.

In sum, high flows, except certain momentary peaks, tend to be greater from the forested watersheds, and low flows lower than from the urban watersheds. The mean peak discharge of 136 c.s.m. from Second River in New Jersey and the greater runoff from summer rainfall attest, presumably, to the efficiency with which paved surfaces deliver runoff to the channel and the lesser opportunity for evapotranspiration. Greater evapotranspiration from the forested areas during the growing season and higher rates of infiltration permit greater storage of summer rainfall and consequently less runoff; thereby more days are required to discharge the 1 and 5 percent of the annual runoff designated as low flow.

The greater high flows from the more northerly forested watersheds (fig. 3) are largely a winter phenomenon; and in part they can be due to the melt of accumulated snow under the influence

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[2] This possible explanation for the low mean momentary peak of the Saddle River was suggested by John E. McCall, District Chief, U. S. Geological Survey, Trenton, N. J., in a personal communication dated 7 January 1969.

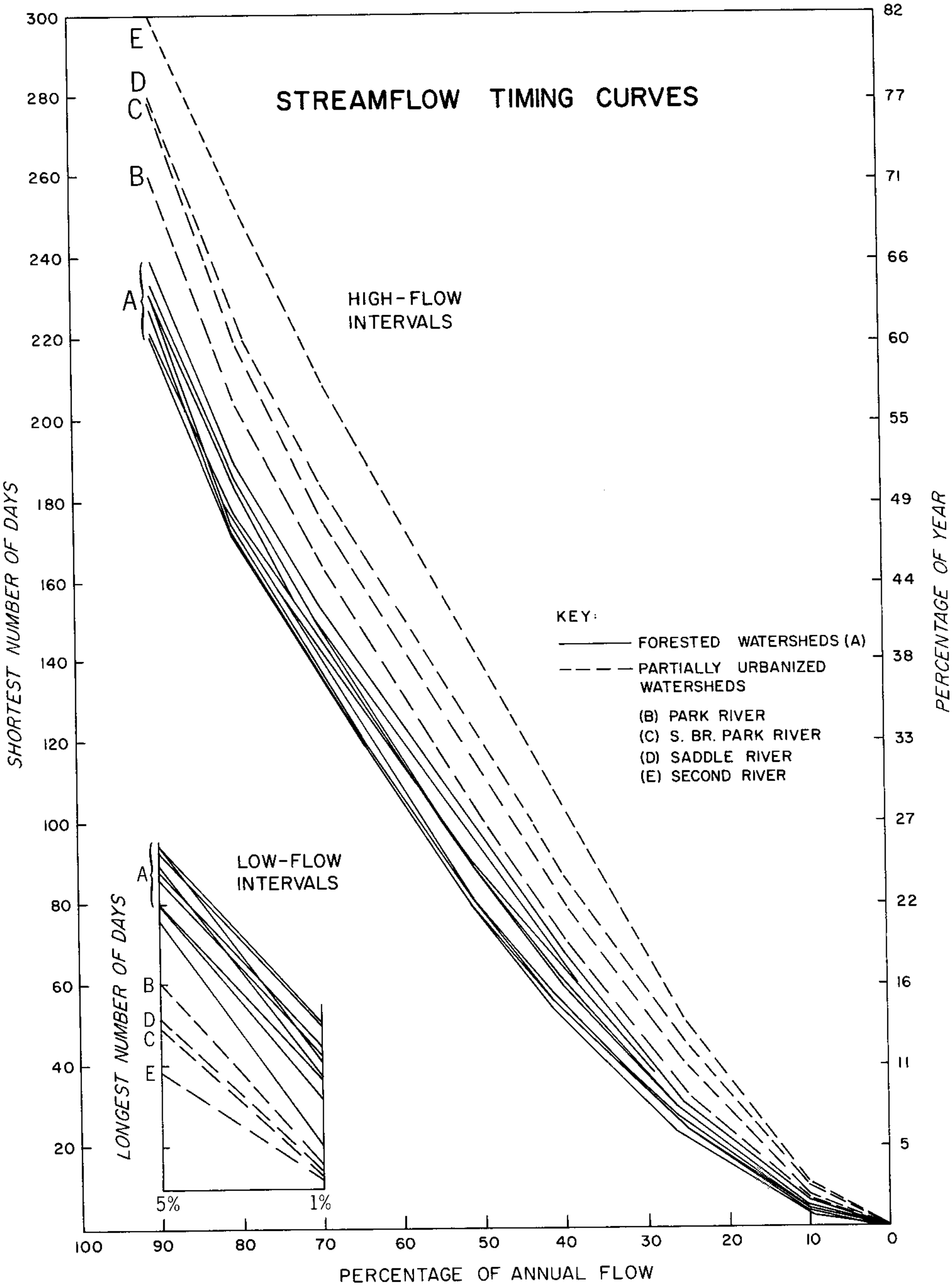


**Figure 4.—Streamflow-timing curves for forested and partially urbanized watersheds in southern New England.**

of winter and early spring thaws. Satterlund and Eschner *(1965)* have shown that rapid melting of accumulated snow under forest stands shortens and concentrates the high-flow period. Under urban conditions, the unshaded snow melts sooner and does not accumulate to the extent it does in forest stands; also, in metropolitan areas some snow on the streets is carted to the river by truck or is melted by salts and soot.

Further, as noted in an earlier study *(Lull and Sopper 1966),* the greater precipitation, steep slopes, and shallow soils of forested watersheds tend to produce greater runoff than can be expected from the lower-lying, less precipitous, deep soils of urban watersheds. The average elevation of the gaging stations of the nine forested watersheds was 521 feet, and for the four urban stations it was 36 feet also, the mean difference in elevations between highest and lowest points was 1,357 feet for the forested and 759 feet for the urban.

Thus, examination of streamflow records of progressively urbanized watersheds, and the comparison of streamflow from partly urbanized watersheds with that from largely forested watersheds, do not indicate the large difference in flows that might be expected theoretically from previous considerations. This may be due principally to the fact that most of the watersheds considered were only partially urbanized, and any urban effects are probably masked by discharge from the substantial non-urban areas.

## CONCLUSIONS

In terms of hydrologic processes, urbanization of forested watersheds would tend to reduce interception, infiltration, soil-moisture storage, and evapotranspiration, and to increase overland flow and runoff. Several studies of peak flows have shown that they may be increased by 1.2 to 5 times over peaks from rural conditions. During development and construction in suburban areas, sedimentation may be increased greatly; and even after construction, sedimentation in these areas may be 5 to 10 times that from protected forested watersheds.

Urbanization effects on potential evapotranspiration and runoff were indicated from simulated applications of various proportions of impervious surfaces on a forested watershed. Annual potential evapotranspiration was reduced an estimated 19, 38, and 59 percent by 25-, 50-, and 75-percent impervious cover, and annual runoff was increased 15, 29, and 41 percent, respectively.

Thirty-year records of streamflow from three progressively urbanized watersheds showed increasing trends in maximum annual peak flows, hydrologic responses, and annual runoff. Maximum daily discharges from watersheds partially urbanized tended to be less both in magnitude and number than the discharges from largely forested watersheds. In addition, the percentage of precipitation that appeared as summer runoff was greater, high-flow intervals were longer, low-flow intervals were shorter, and hydrologic responses were greater from the partially urbanized areas.

We may conclude that urbanization of forested watersheds can have profound effects on hydrologic processes when they are considered individually; and, theoretically, urbanization can greatly increase runoff and peak flows. However, comparisons of actual streamflow records of partially urbanized watersheds with those from forested watersheds less than 100 square miles in area suggest that the effects of urbanization will appear principally in the greater percentage of rainfall that appears as summer runoff and in higher low flows during the summer-fall season.

Our results were inconclusive with respect to high flows during the winter-spring season, at least partly because of latitude and elevation differences between the forested and urbanized watersheds selected for this study.

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