Hydrology for Urban Land Planning—
A Guidebook on the Hydrologic
Effects of Urban Land Use

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Effects of Urban Land Use

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HYDROLOGY FOR URBAN LAND PLANNING—A GUIDEBOOK ON THE HYDROLOGIC EFFECTS OF URBAN LAND USE

By Luna B. Leopold

This circular attempts to summarize existing knowledge of the effects of urbanization on hydrologic factors. It also attempts to express this knowledge in terms that the planner can use to test alternatives during the planning process. Because the available data used in this report are applied to a portion of the Brandywine Creek basin in Pennsylvania, this can be considered as a report on the basic hydrologic conditions of the Brandywine Creek basin prior to the beginning of major urbanization. Because the available data are not yet adequate, this report can be considered as a compilation of tentative suggestions in the form of an explanatory, not a definitive, handbook.

The application of current knowledge of the hydrologic effects of urbanization to the Brandywine should be viewed as a forecast of conditions which may be expected as urbanization proceeds. By making such forecasts in advance of actual urban development, the methods can be tested, data can be extended, and procedures improved as verification becomes possible.

PLANNING PROCEDURES AND HYDROLOGIC VARIABLES

A planning document presented to a community for adoption must always be more suggestive than coercive. This is true not only because the planner is unable to foresee the innumerable complications of actual development, but also because there are many detailed alternatives which would accomplish generally similar results. The planner is particularly concerned with both the constraints and the opportunities offered by the principal physiographic characteristics of the area, especially the location of hillslopes, soils, and streams. The existing pattern of land use and the accompanying distribution of woods and agriculture are parameters which over a period of years may actually change, albeit slowly. Roads, villages, industries, and other manmade features are more or less permanent and exert their greatest influence in their effect on further development, especially through land values.

Of particular concern to the planner are those alternatives that affect the hydrologic functioning of the basins. To be interpreted hydrologically, the details of the land-use pattern must be expressed in terms of hydrologic parameters which are affected by land use. These parameters in turn become hydrologic variables by which the effects of alternative planning patterns can be evaluated in hydrologic terms.

There are four interrelated but separable effects of land-use changes on the hydrology of an area: changes in peak flow characteristics, changes in total runoff, changes in quality of water, and changes in the hydrologic amenities. The hydrologic amenities are what might be called the appearance or the impression which the river, its channel and its valleys, leaves with the observer. Of all land-use changes affecting the hydrology of an area, urbanization is by far the most forceful.

Runoff, which spans the entire regimen of flow, can be measured by number and by characteristics of rise in streamflow. The many

rises in flow, along with concomitant sediment loads, control the stability of the stream channel. The two principal factors governing flow regimen are the percentage of area made impervious and the rate at which water is transmitted across the land to stream channels. The former is governed by the type of land use; the latter is governed by the density, size, and characteristics of tributary channels and thus by the provision of storm sewerage. Stream channels form in response to the regimen of flow of the stream. Changes in the regimen of flow, whether through land use or other changes, cause adjustments in the stream channels to accommodate the flows.

The volume of runoff is governed primarily by infiltration characteristics and is related to land slope and soil type as well as to the type of vegetative cover. It is thus directly related to the percentage of the area covered by roofs, streets, and other impervious surfaces at times of hydrograph rise during storms.

A summary of some data on the percentage of land rendered impervious by different degrees of urbanization is presented by Lull and Sopper (1966). Antoine (1964) presents the following data on the percentage of impervious surface area in residential properties:

Lot size of residential area (sq ft)	Impervious surface area (percent)
6,000	80
6,000–15,000	40
15,000	25

The percentage decreases markedly as size of lot increases. Felton and Lull (1963) estimate in the Philadelphia area that 32 percent of the surface area is impervious on lots averaging 0.2 acre in size, whereas only 8 percent of the surface area is impervious on lots averaging 1.8 acres.

As volume of runoff from a storm increases, the size of flood peak also increases. Runoff volume also affects low flows because in any series of storms the larger the percentage of direct runoff, the smaller the amount of water available for soil moisture replenishment and for ground-water storage. An increase in total runoff from a given series of storms as a result of imperviousness results in decreased ground-

water recharge and decreased low flows. Thus, increased imperviousness has the effect of increasing flood peaks during storm periods and decreasing low flows between storms.

The principal effect of land use on sediment comes from the exposure of the soil to storm runoff. This occurs mainly when bare ground is exposed during construction. It is well known that sediment production is sensitive to land slope. Sediment yield from urban areas tends to be larger than in unurbanized areas even if there are only small and widely scattered units of unprotected soil in the urban area. In aggregate, these scattered bare areas are sufficient to yield considerable sediment.

A major effect of urbanization is the introduction of effluent from sewage disposal plants, and often the introduction of raw sewage, into channels. Raw sewage obviously degrades water quality, but even treated effluent contains dissolved minerals not extracted by sewage treatment. These minerals act as nutrients and promote algae and plankton growth in a stream. This growth in turn alters the balance in the stream biota.

Land use in all forms affects water quality. Agricultural use results in an increase of nutrients in stream water both from the excretion products of farm animals and from commercial fertilizers. A change from agricultural use to residential use, as in urbanization, tends to reduce these types of nutrients, but this tendency is counteracted by the widely scattered pollutants of the city, such as oil and gasoline products, which are carried through the storm sewers to the streams. The net result is generally an adverse effect on water quality. This effect can be measured by the balance and variety of organic life in the stream, by the quantities of dissolved material, and by the bacterial level. Unfortunately data describing quality factors in streams from urban versus unurbanized areas are particularly lacking.

Finally, the amenity value of the hydrologic environment is especially affected by three factors. The first factor is the stability of the stream channel itself. A channel, which is gradually enlarged owing to increased floods caused by urbanization, tends to have unstable and unvegetated banks, scoured or muddy

channel beds, and unusual debris accumulations. These all tend to decrease the amenity value of a stream.

The second factor is the accumulation of artifacts of civilization in the channel and on the flood plain: beer cans, oil drums, bits of lumber, concrete, wire—the whole gamut of rubbish of an urban area. Though this may not importantly affect the hydrologic function of the channel, it becomes a detriment of what is here called the hydrologic amenity.
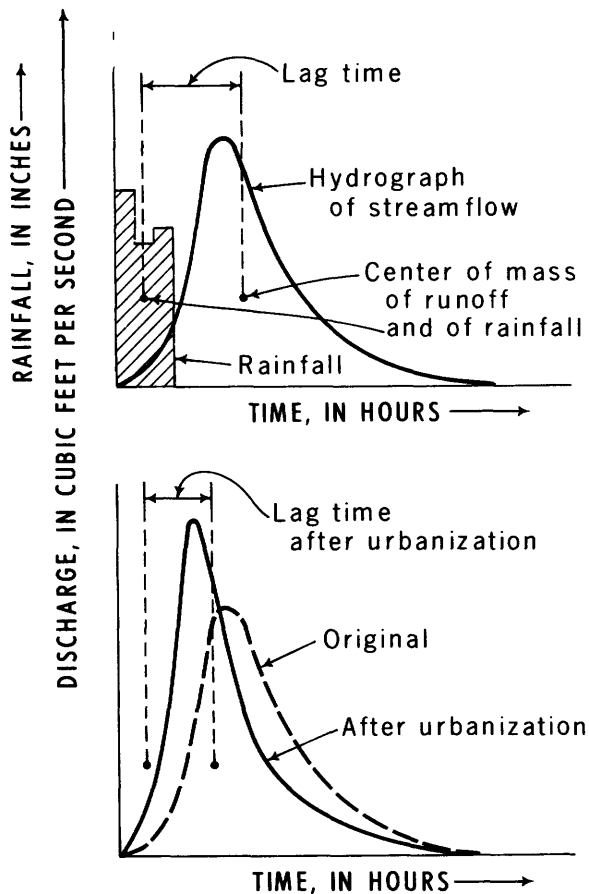

Figure 1.—Hypothetical unit hydrographs relating runoff to rainfall, with definitions of significant parameters.

The third factor is the change brought on by the disruption of balance in the stream biota. The addition of nutrients promotes the growth of plankton and algae. A clear stream, then, may change to one in which rocks are covered with slime; turbidity usually increases, and odors may develop. As a result of increased turbidity and reduced oxygen content desirable

game fish give way to less desirable species. Although lack of quantitative objective data on the balance of stream biota is often a handicap to any meaningful and complete evaluation of the effects of urbanization, qualitative observations tend to confirm these conclusions.

AVAILABILITY OF DATA AND THE TECHNIQUE OF ANALYSIS

Basic hydrologic data on both peak flow and volume of runoff may be expressed in terms of the characteristics of the unit hydrograph, that is, the average time distribution graph of flow from a unit or standard storm. The unit hydrograph shows the percentage of the total storm runoff occurring in each successive unit of time. The standard storm may be, for example, a typical storm which produced 1 inch of runoff (fig. 1). Such data are derived from the study of individual storms and the associated runoff graphs measured at gaging stations.

One factor stating the relation between the storm and the runoff is lag time. This is defined as the time interval between the center of mass of the storm precipitation and the center of mass of the resultant hydrograph. Lag time is a function of two basin parameters—the mean basin slope and the basin length. These factors empirically correlate with lag time if expressed in the form of the basin ratio (basin length L divided by the square root of the mean basin gradient, s). This basin ratio is also related to drainage area. As drainage area increases, the basin length increases and the average value of slope generally decreases. Thus, natural basin characteristics can be translated into flood-flow characteristics.

Lag time may be materially altered by the effects of urbanization on the basin surface. Water runs off faster from streets and roofs than from natural vegetated areas. This tends to decrease the lag time. The construction of artificial channels, especially storm sewers, also decreases lag time. As the time required for a given amount of water to run off shortens, the peak rate of runoff (flood peak) increases.

In addition to the basin ratio and lag time, the regimen of a stream, however, can be described in many other ways, including flood

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frequency, flow duration, mean annual flood, discharge at bankfull stage, and frequency of bankfull stage. This is evidenced in past studies of the effects of urbanization on the hydrology of an area. Many different techniques of relating rainfall to runoff have been used, along with various parameters to measure the degree of urbanization. In order to evaluate our present knowledge, it is necessary to express the results of these studies in some common denominator.

Most reports on hydrologic effects of urbanization present the conclusions in a form which is more useful to the hydrologist than to the urban planner. This circular will attempt to interpret the hydrologic conclusions of these studies in terms that are meaningful to the planner. Two forms of presentation will be used.

The first is a slight modification of a method previously used by several investigators, especially D. G. Anderson (1968) and L. D. James (1965). The percentage of an area sewered is plotted against the percentage of the area rendered impervious by urbanization; isopleth lines (lines of equal value of the ratio) on the graph show the ratio of peak discharge under urbanized conditions to the peak discharge under rural or unurbanized conditions. Such a graph will be different for different drainage area sizes and for different flow frequencies.

The second method utilizes a relationship between the degree of urbanization and the frequency at which the original channel capacity would be exceeded.

Table 1 is an interpretation and summary of the effects of urbanization on peak discharges based on previous studies. Results of the studies were interpreted and extrapolated to a common denominator of 1 sq mi (square mile), a practical unit of size for planning.

Carter (1961) developed a technique that followed the reasoning previously used by Snyder (1938) and that showed lag time as a function of basin characteristics. For 20 streams in the vicinity of Washington, D.C., Carter developed this relation for natural basins, for partly sewered, and for completely sewered basins. As in most studies the difficulty comes in translating these descriptive terms to quantitative measures of urbanization. From data presented by Carter, values were read for a basin ratio of 0.12 representing a 1-sq-mi area having an estimated length of 1.2 miles and an average slope of 100 feet per mile. It was further assumed that in Carter's study, "partly sewered" is equivalent to 50 percent sewered and 20 percent impervious. These conditions provide some of the data shown in table 1.

Table 1.—*Increase in discharge as a result of urbanization in a 1-square-mile area*

[Discharge is mean annual flood; recurrence interval is 2.3 years. Data are expressed as ratio of discharge after urbanization to discharge under previous conditions. Data from James (1965) have no superscript]

Percentage of area served by storm sewerage	Percentage of area made impervious			
	0	20	50	80
0	1.0	[1]1.2	[1]1.8	[1]2.2
		[2]1.3	[2]1.7	[2]2.2
		1.3	1.6	2.0
20	1.1	[3]1.9	1.8	2.2
		1.4	—	—
50	1.3	[4]2.1	[1]3.2	[1]4.7
		[1]2.8	2.0	2.5
		[5]3.7	—	—
		[6]2.0	2.5	[3]4.2
		1.6	—	—
80	1.6	1.9	—	3.2
100	1.7	[1]3.6	[1]4.7	[4]5.6
		2.0	2.8	[1]6.0
		—	—	3.6

[1] Anderson (1968).　[5] Wiitala (1961).
[2] Martens (1966).　[6] Espey, Morgan, and Masch
[3] Wilson (1966).　(1966).
[4] Carter (1961).

As an indication of the change in impervious area resulting from urbanization, Harris and Rantz (1964) showed that an area near Palo Alto, Calif., changed from 5.7 percent to 19.1 percent impervious in a 10-year period.

One of the most complete analyses of urbanization effects was made by D. G. Anderson (1968) in his study of the urbanization in Fairfax County, Va., near the metropolitan complex of the Nation's Capital. Anderson's analysis follows the procedure suggested earlier by Carter, but Anderson included a larger array of data from 64 gaging stations. Anderson closely confirmed the conclusions of Carter, but he carried the analysis further in a plot of

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the ratio of peak discharge to the mean annual flood for different percentages of basin imperviousness and for flood flows exceeding the mean annual flood. For table 1, data from Anderson's study were read directly from his graph at the 2.33-year recurrence interval and expressed two separate conditions of sewerage. The first condition was expressed as "main channels natural, upstream drainage sewered"; this was assumed to be 50 percent sewered. The second condition was expressed as "completely sewered drainage basin"; this was assumed to be 100 percent sewered.

Wiitala (1961) presented data on urbanized versus rural conditions for a medium-sized watershed in Michigan. His data were translated into a ratio of peak discharges and it was assumed from his report that the urbanized condition represented 20 percent impervious area and 50 percent sewered area.

Martens (1966) reported on three small drainage basins in and near Charlotte, N.C. Using flood-frequency curves from long-term records at gaging stations in the State, he constructed a graph similar to that of Anderson; that is, ratio to mean annual flood for various degrees of basin imperviousness. As before, the difficulty lies in ascertaining the relation of Martens' urbanized condition to the degree sewered. In reading from Martens' graph for recurrence interval 2.33 years, it is assumed that the conditions he discussed include no sewerage and represent changes in impervious area only.

Wilson (1966) presented data on flood frequency for four drainage basins of 1.1 to 11.2 sq mi near Jackson, Miss. He presented his analysis in the form of discharge of mean annual flood plotted against drainage area size, and he interpolated lines to represent the percentage of the basin having storm sewers and improved channels. It is assumed that his description "20 percent of basin with storm sewers and improved channels" would be equivalent to 20 percent impervious and 20 percent sewered. Similarly, his value of 80 percent was assumed to be 80 percent sewered and 80 percent impervious.

Espey, Morgan, and Masch (1966) analyzed runoff data from urban and rural areas in Texas. To utilize this study, data were used corresponding to a basin length of 5,500 feet and a slope of 0.02. It was also assumed from his description of the area that "urban" could be expressed as 50 percent sewered and 20 percent impervious.

James (1965) analyzed runoff data from a 44-sq-mi basin south of Sacramento, Calif., within which 12 sq mi had been urbanized. From the basic data on flow, he obtained empirical coefficients used to route a series of synthetic flows by using a mathematical model expressed as a digital computer program. The results were plotted in a series of curves which separated the effects of flood frequency, drainage area, and degree of urbanization. Though the derived curves do not present field data, they also were incorporated into table 1.

Thus in table 1 are compiled, with certain necessary assumptions, the data for seven published and unpublished references which report measurements of the effect of urbanization on peak flow. Although interpretations were necessary to express the degree of urbanization in quantitative terms, there is considerable agreement among the data.
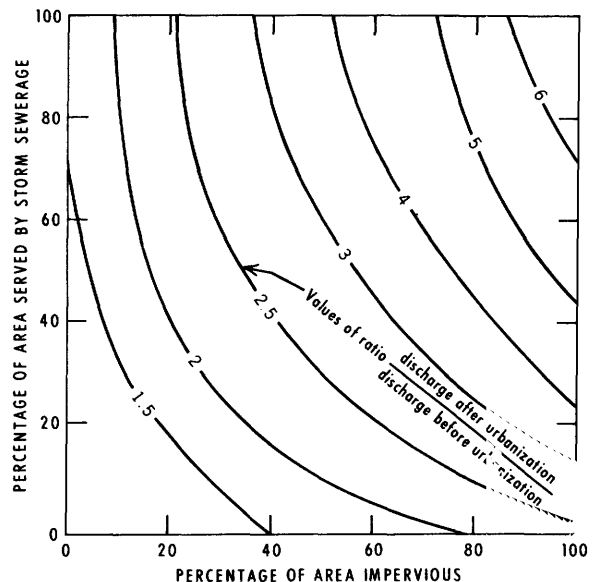

Figure 2.—Effect of urbanization on mean annual flood for a 1-square-mile drainage area. (Based on data from table 1.)

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Data from table 1 have been transposed into the graph shown in figure 2. The ratios of peak discharge of urbanized to rural areas are presented for different percentages of sewerage and impervious area; lines of equal values of the ratio are drawn through the data. Briefly, these data show that for unsewered areas the differences between 0 and 100 percent impervious will increase peak discharge on the average 2.5 times. For areas that are 100 percent sewered, peak discharge for 0 percent impervious will be about 1.7 times the mean annual flood and the ratio increases to about eight for 100 percent impervious areas. Figure 2, then, reduces the basic data to the same units applicable to a 1-sq-mi drainage basin and to the mean annual flood.

A basin produces big flows from large and intense storms and smaller flows from less intense but more frequent storms. The great or catastrophic event is rare, and the storm of ordinary magnitude is frequent. These events can be arranged in order of magnitude and counted. For example, all discharge events exceeding 400 cfs (cubic feet per second) can be tabulated from the record at a stream-gaging station and arranged in order of magnitude; the values in the array can be plotted as a discharge-frequency curve. This has been done for the gaging station on West Branch Brandywine Creek at Coatesville, Pa., for 9 years of record (fig. 3). The theory and practice of constructing such flow-frequency curves is well known. The plotting position or frequency often used is defined as

$$R = \frac{n+1}{m}$$

where R is the recurrence interval in years, n is number of years of record, and m is the rank of the individual event in the array.
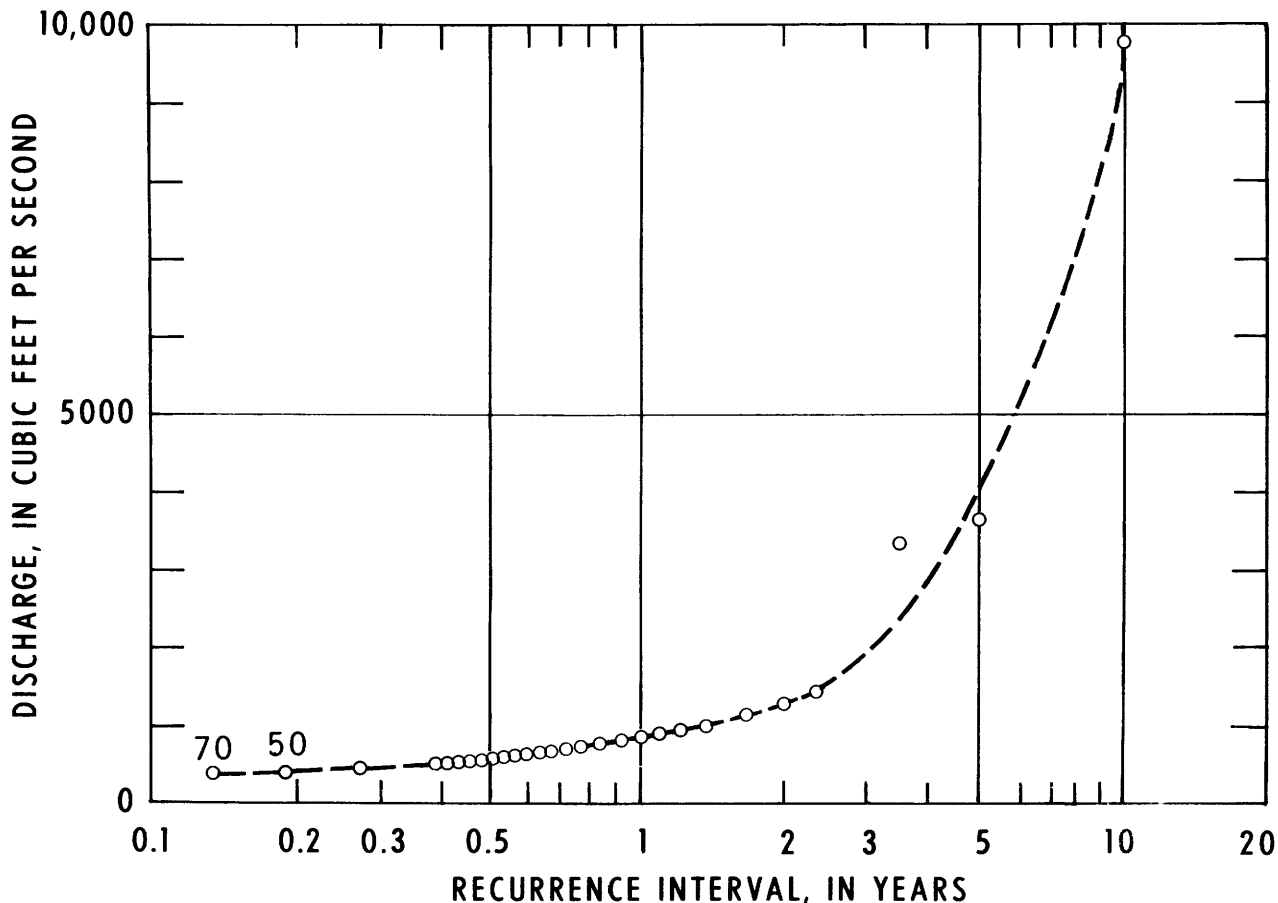

Figure 3.—Flood-frequency curve for partial-duration series, West Branch Brandywine Creek at Coatesville, Pa., based on data for 1942, 1944–51.

Note in figure 3 that the largest flow in the 9-year record was nearly 10,000 cfs. The number 50 printed on the graph means that there were 50 flows equal to or exceeding 500 cfs. Once a year, on the average, a discharge value of about 900 cfs will be equalled or exceeded.

A slightly different result would be obtained if, instead of using the peak flow for each storm, only the largest flow in each year were included in the array. The principle involved is similar. The arithmetic mean of the peak flows for the nine annual events is the "average annual flood." The statistics of this array are such that the recurrence interval of this average annual flood is the same regardless of the length of record, which specifically is 2.3 years. That is to say, a flood of that magnitude can be expected to be equaled or exceeded on an average of once in 2.3 years, or 10 times in 23 years.

Studies of river channels have shown that rivers construct and maintain channels which will carry without overflow a discharge somewhat smaller than the average annual flood. In fact the recurrence interval of the bankfull stage in most rivers is a flow having a recurrence interval of about 1.5 to 2 years.

Urbanization tends to increase the flood potential from a given basin. The channel then will receive flows which exceed its capacity not just once in 1.5 to 2 years on the average but more often. It is now proposed to estimate how much more often and to indicate the effect of this increased frequency on the channel itself.

EFFECT OF URBANIZATION ON INCREASING FREQUENCY OF OVERBANK FLOW

Taking the East Branch of Brandywine Creek as an example, the flow-frequency curve can be constructed for a typical subbasin having a 1-sq-mi drainage area. Figure 4A shows the relation of average annual flood to drainage area, and figure 4B shows the flood-frequency curve for annual peaks for basins in the Brandywine area. The diagrams shown in figure 4 are similar to those published in the nationwide series of flood reports, U.S. Geological Survey Water-Supply Papers 1671–1689.

From these curves a discharge-frequency relationship is developed for a drainage area of

1 sq mi. The average annual flood is read from the upper graph of figure 4 as 75 cfs, and the lower graph is used to construct the frequency curve in figure 5 pertaining to a 1-sq-mi basin marked "unurbanized."

The arithmetic for the construction of the curve is as follows:

Recurrence interval of annual flood [1] (years)	Ratio to mean annual flood [2]	Discharge [3] (cfs)	Recurrence interval duration series [4] (years)
1.1	0.55	41	0.4
1.5	.75	56	.92
2.0	.90	68	1.45
2.3	1.0	75	1.78
5	1.45	110	4.5
10	1.9	145	9.5

[1] Only the highest flood each year.
[2] From figure 4B.
[3] Obtained by multiplying ratios by 75 cfs from figure 4A for a drainage area of 1 sq mi.
[4] All peaks during the year. The values in this column are mathematically related to those in the first.

The graph marked "unurbanized" in figure 5 is constructed on semilogarithmic paper from the data listed in the third and fourth columns of the preceding table. The ordinate is the discharge, and the lower abscissa is the recurrence interval in the duration series. An auxiliary scale gives the average number of floods in a 10-year period (calculated as 10 years divided by the recurrence interval). Thus, the flow expected to occur once in 10 years would be about 145 cfs and the fifth largest would be 75 cfs. The latter would also be the average value of the largest flows each year during the 10-year record and thus would be the "average annual flood." It would plot, therefore, at an abscissa position approximately at 2.3-year recurrence interval.

The effect of urbanization on the average annual flood is shown in figure 2, which shows the increase in average annual flood for different degrees of urbanization as measured by the increase in percentages of impervious area and area served by storm sewers. For convenience these are tabulated as follows:

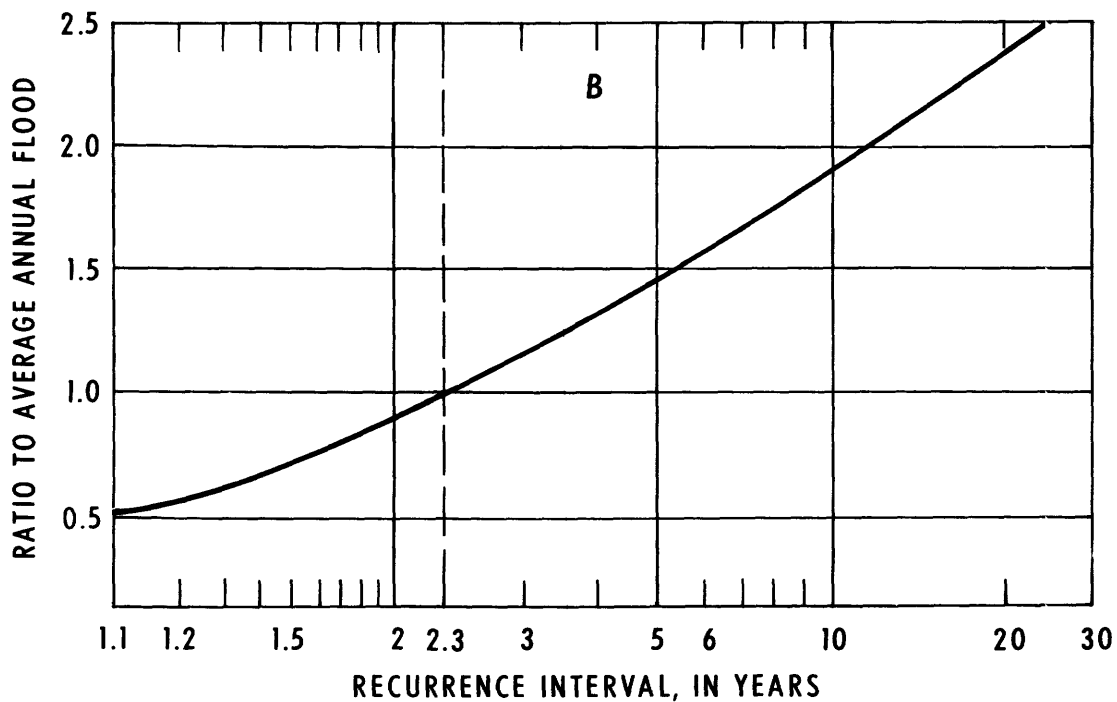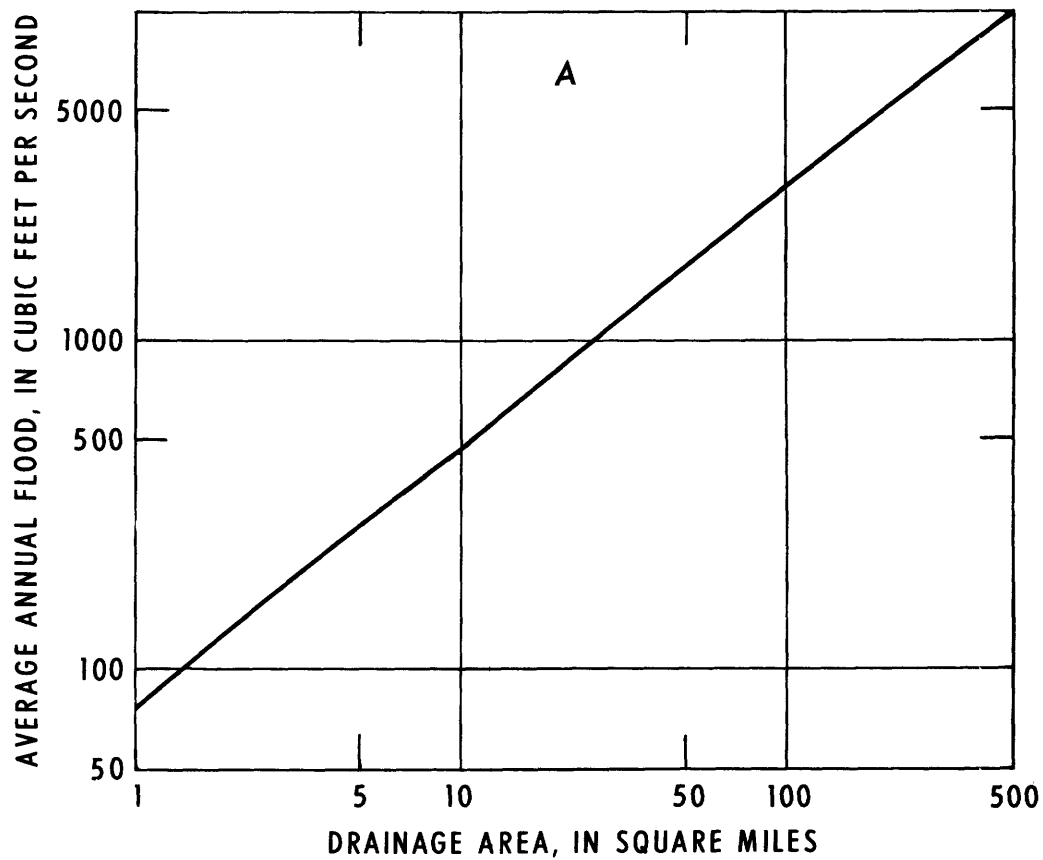| Percentage of area sewered	Percentage of area impervious	Ratio to average annual flood
0	0	1
20	20	1.5
40	40	2.3
50	50	2.7
80	60	4.2
100	60	4.4

Figure 4.—Regional flood-frequency data for the Brandywine Creek basin, Pennsylvania. *A*, Relation of average annual flood to drainage area. *B*, Flood-frequency curve for annual peaks.
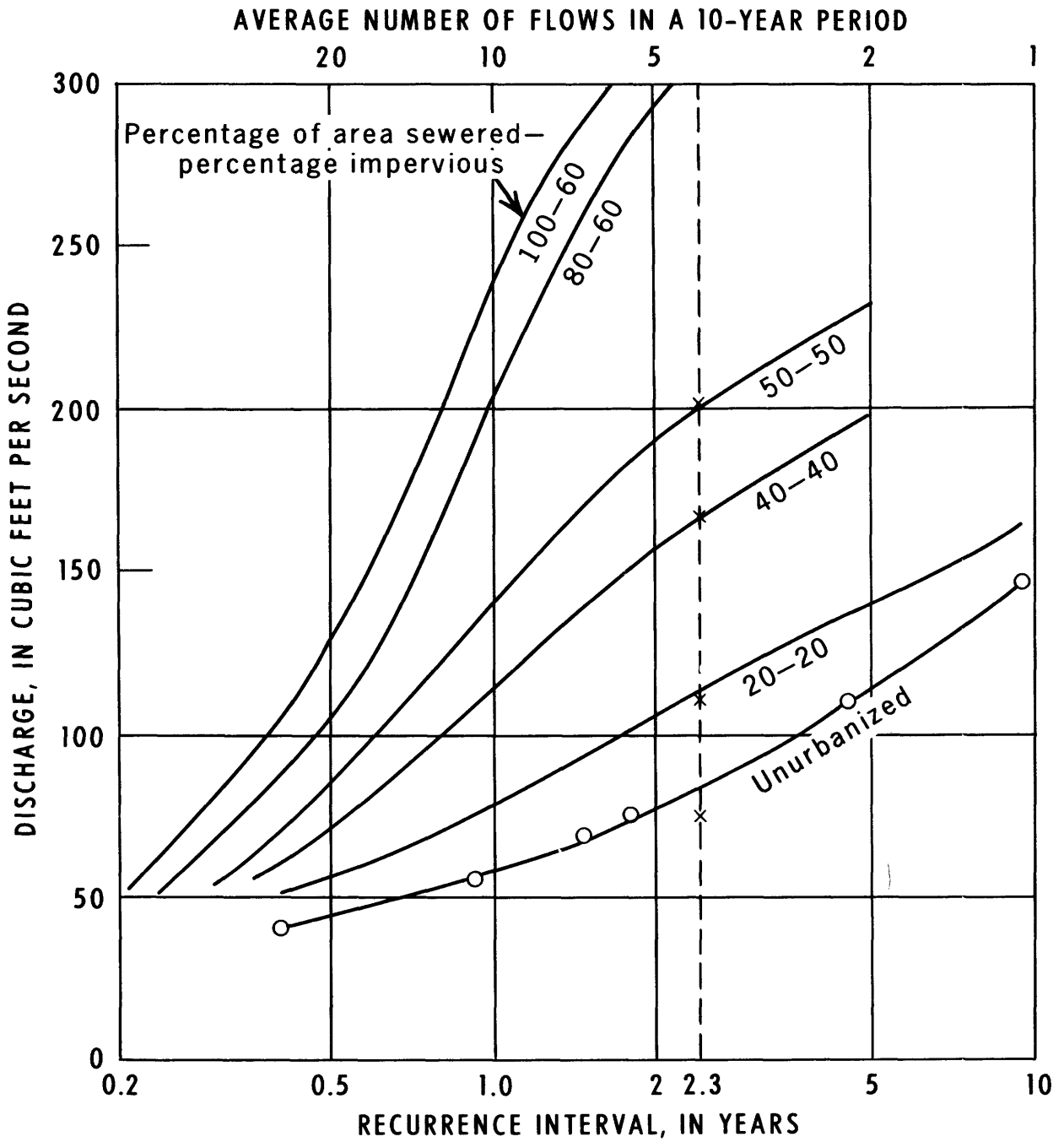
Figure 5.—Flood-frequency curves for a 1-square-mile basin in various states of urbanization. (Derived from figures 2 and 4.)

The average annual flood of 75 cfs was then multiplied by these ratios and plotted as shown in figure 5 at the 2.3-year interval. These values form the basis of a series of frequency curves for combinations of sewered area and impervious area. The shapes of the curves are guided by the principle that the most infrequent floods occur under conditions that are not appreciably affected by imperviousness of the basin.

The most frequent flows are therefore increased by smaller ratios than would be the average annual flood. Also, the most frequent flows are decreased in number because low flows from an urbanized area are not sustained by ground water as in a natural basin. The curves representing urbanized conditions therefore converge at low flow values.

Obviously the frequency curves in figure 5 are extrapolations based on minimal data and require corroboration or revision as additional field data become available.

The flood-frequency curve under original (unurbanized) condition passes through a value of 67 cfs at a recurrence interval of 1.5 years. At bankfull condition natural channels generally can carry the flow having that recurrence interval. If one assumes that this flow approximates the capacity of the natural channels, the intersection of the estimated curves for different degrees of urbanization with the discharge value of 67 cfs can be used to estimate the in-
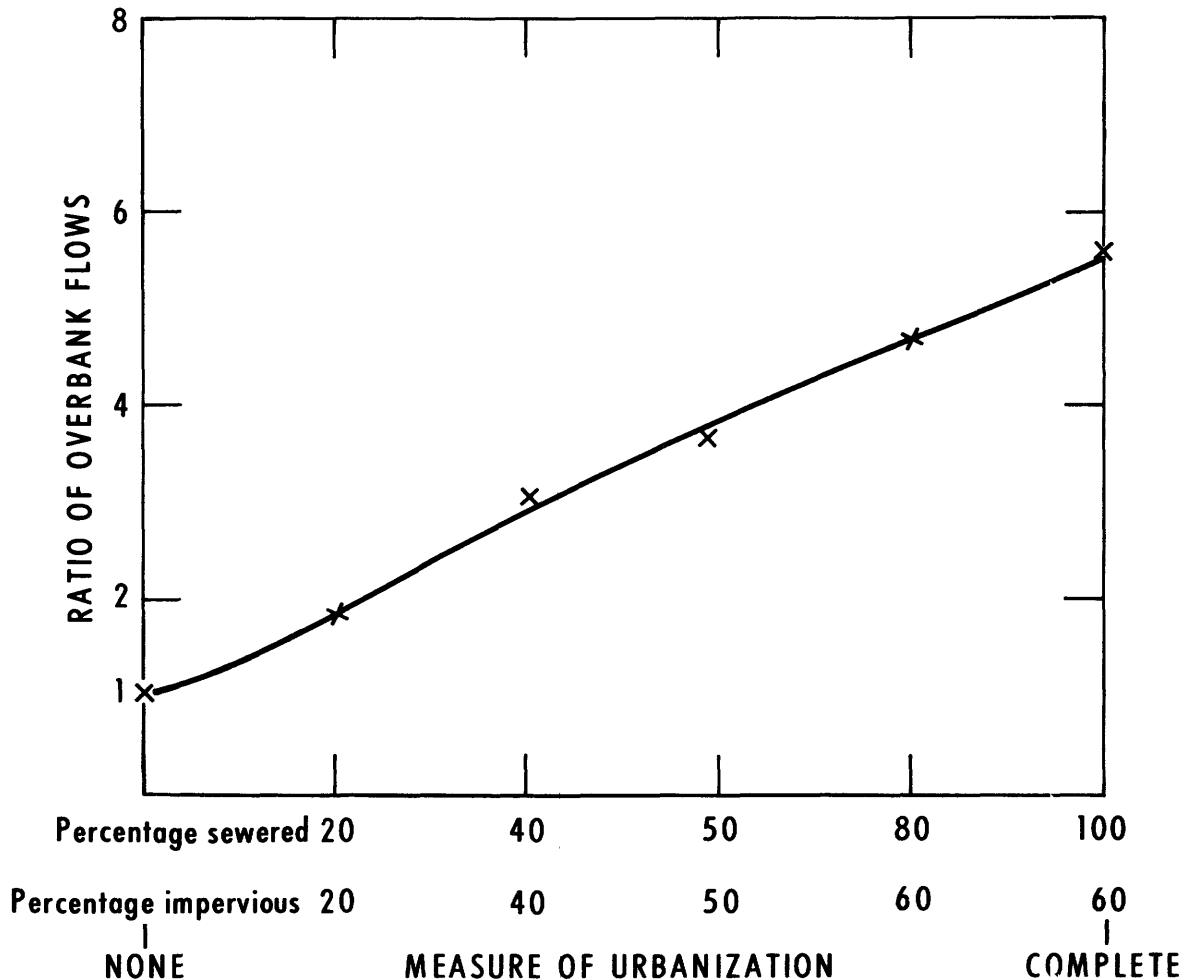

Figure 6.—Increase in number of flows per year equal to or exceeding original channel capacity (1-square-mile drainage area), as ratio to number of overbank flows before urbanization, for different degrees of urbanization. (Derived from figure 5.)

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crease in number of flows equal to or exceeding natural channel capacity. An auxiliary scale is shown at the top of figure 5 to facilitate this.

For example, under natural conditions it is expected that a 10-year record would show about seven flows equal to or exceeding 67 cfs, or channel capacity. But if the average annual flood were increased 1.5 times (from 75 to 112 cfs) corresponding to 20 percent sewered and 20 percent impervious, the new frequency curve indicates that 14 flows of 67 cfs or greater would occur in a 10-year period, or a twofold increase in number of flows. Similarly, the ratio of number of flows exceeding bankfull capacity was read from the intersection of the other curves in figure 5 with the ordinate value of 67 cfs to obtain the ratios plotted in figure 6.

Figure 6 shows that with an area 50 percent sewered and 50 percent impervious, for example, the number of flows equal to or exceeding bankfull channel capacity would, over a period of years, be increased nearly fourfold.

LOCAL STORAGE TO COMPENSATE FOR PEAK FLOW INCREASE

Urbanization tends to increase both the flood volume and the flood peak. But the increase can be compensated so that the discharge through channels downstream is maintained to any degree desired within the range which existed prior to urbanization. It is obvious that reservoir storage is installed on a river in order to reduce the magnitude of peak discharge by spreading the flow over a longer time period. Channels themselves provide temporary storage and act as if they were small reservoirs. Overbank flooding on to the flat flood plain is a way that natural rivers provide for temporary storage and thus decrease flood peaks downstream. This effect of storage has been fully investigated and described (for example see Leopold and Maddock, 1954, especially p. 36–49).

The provision of flood storage upstream, then, will decrease flood peaks and compensate for the increase caused by urbanization. This storage could take many forms including the following:
1. Drop inlet boxes at street gutter inlets.
2. Street-side swales instead of paved gutters and curbs.
3. Check dams, ungated, built in headwater swales.
4. Storage volumes in basements of large buildings receiving water from roofs or gutters and emptying into natural streams or swales.
5. Off channel storage volumes such as artificial ponds, fountains, or tanks.
6. Small reservoirs in stream channels such as those built for farm ponds.

Various types of storage volumes could be used simultaneously in various mixes. The effectiveness depends on the volume of storage relative to the volume of inflow during a storm peak period. Design criteria to guide city engineers and developers are needed.

SEDIMENT PRODUCTION

The basic data available for analyzing the effect of urbanization on sediment yield, though sparse, have been summarized to some extent in the literature. Especially valuable is the report by Wolman (1964) who summarized not only the data obtained from sediment sampling stations in streams in Eastern United States but also studied the sediment yield from building construction activities. Sediment yields from urbanized or developing areas ranged from 1000 to more than 100,000 tons per square mile per year.

It should be recognized that sediment yield per square mile decreases with increasing drainage area, but nevertheless it is apparent that unurbanized drainage basins yield 200 to 500 tons per square mile per year, on the average. These figures are slightly higher for the farmed Piedmont lands, which may be expected to produce sediment yield of 500 tons per square mile per year, such as the Watts Branch basin near Rockville, Md.

The data on urbanized areas studied by Wolman are plotted in figure 7 together with data from suspended load sampling stations of the U.S. Geological Survey as summarized by Wark and Keller (1963).

In the graph (fig. 7) three bands or zones are labeled A, C, and UC. Wolman and Schick (1967) differentiated the following types of activity: A, agricultural or natural; C, under-
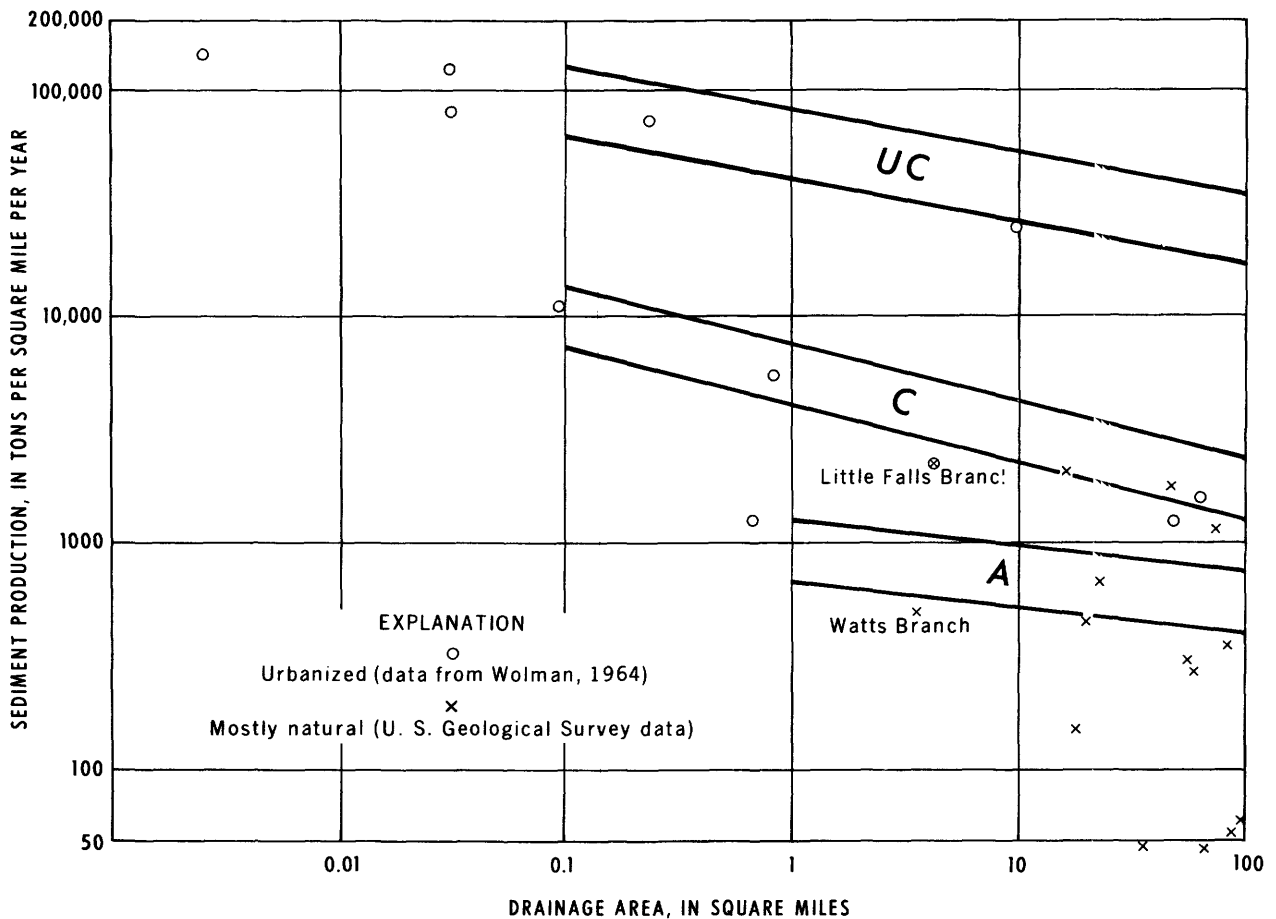
Figure 7.—Annual sediment production per square mile for urbanized and natural areas. Zon·s: *A*, agricultural; *C*, under construction; *UC*, under construction and undiluted.

going building construction, but highly diluted before reaching channels; and *UC*, undiluted sediment yields delivered to stream channels from construction sites.

They found that when building sites are denuded for construction, excavations are made, and dirt is piled without cover or protection near the site, the sediment movement in a rill or stream channel is very large in terms of tons per year immediately downhill from the construction site. If the channel contains little water except during storms (an ephemeral stream), there is no chance for dilution; during storm flow the sediment movement is great. If the construction debris gets into perennial channels, or for other reasons is distributed along a channel or dispersed over a wide area, the dilution lowers the yield per square mile

per year. Thus, Wolman and Schick drew the distinction between agricultural, construction, and construction-undiluted.

For very small areas, Wolman (1964) said, "Because construction denudes the natural cover and exposes the soil beneath, the tonnage of sediment derived by erosion frcm an acre of ground under construction in deve'opments and highways may exceed 20,000 to 40,000 times the amount eroded from farms and wo〕dlands in an equivalent period of time."

Figure 7 shows the data as a relation between annual sediment yield per square mile and drainage basin size. The usual suspended load station is on a basin of more than 10 sq mi in area. Seldom is urbanization complete for basins of this size.
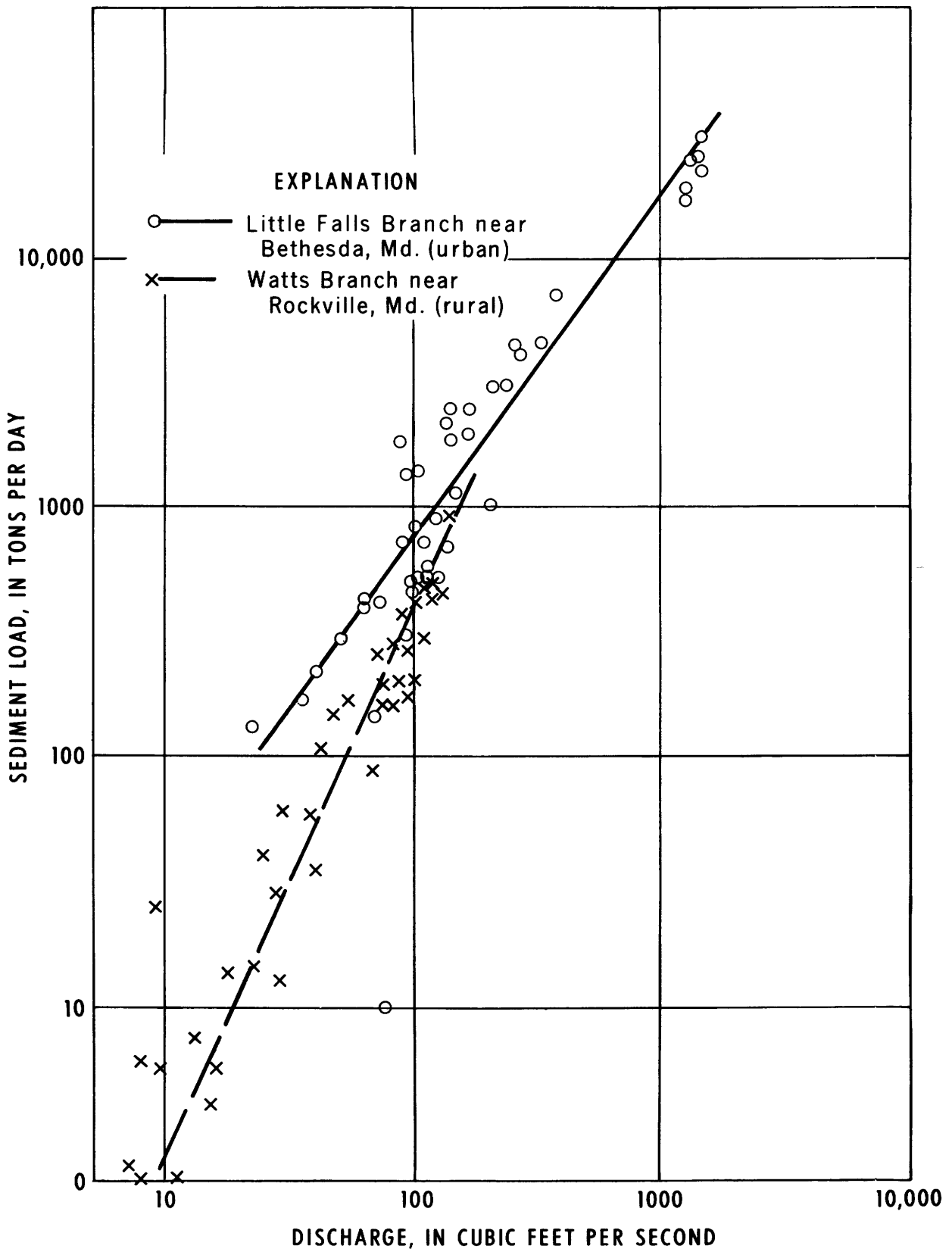
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Figure 8.—Relation of sediment yield and discharge for an urban and a rural or unurbanized area.

The data measured or estimated by Wolman (1964) in small urbanizing, developed or industrial areas show clearly that the sediment yield is larger by 10 to 100 times that of rural areas. Guy and Ferguson (1962) observed an increase of 250 times in an area near Kensington, Md.

To illustrate the difference in sediment samples obtained during storm flow, actual data for two stations are shown in figure 8. The sediment rating curve, which is a plot of the discharge at any moment in time against the concurrent rate of sediment transport, gives an indication of the order of magnitude of the increase in sediment production from developed, as against rural, areas. The sediment rating curves in figure 8 are for stations near Washington, D.C. Watts Branch drains an area primarily used for farming though urban influences have recently extended into the basin. Little Falls Branch near Bethesda drains a nearly completely urbanized community, consisting of Bethesda and parts of Chevy Chase, Md.

Note that the sediment rating curves tend to converge at high discharges. One might suppose that at those discharges the urbanized areas are actually contributing no more sediment than the unurbanized ones. This is not the case, however, owing to the fact that as a result of urbanization, the number of high flows increases materially. Because most of the sediment during the year is carried during periods of high flow, the result is that urbanized areas yield on the average larger sediment loads than the unurbanized ones.

The difference in drainage basin size between Watts Branch (3.7 sq mi) and Little Falls Branch (4.1 sq mi) is not alone sufficient to explain the larger discharges in the latter basin. For about the same number of sample storms, note that Little Falls Branch data include discharges varying from 20 to 1500 cfs. In contrast, Watts Branch data (unurbanized) include flows ranging from 7 to 150 cfs. At least some of this difference is probably due to the effect of urbanization on increasing peak flow from a storm of given size, as discussed earlier. The two basins are only 10 miles apart and storms are comparable.

Keller (1962) compared the sediment rating curves for Northwest Branch of Anacostia River near Colesville, Md., a relatively unurbanized basin, and the Anacostia River basin near Hyattsville, Md., which is partly urbanized. He found the sediment production to be about four times greater in the urbanized area.

Most sediment carried by a stream is moved by high flows. In Brandywine Creek, for example, about 54 percent of the total sediment transported annually by the river (drainage area 312 sq mi) is carried by flows that occur, on the average, about 3 days each year.

In the tabulation below, a comparison is made between sediment yield from Watts Branch, a rural landscape, and Little Falls Branch, an urban one. These basins are of the size and type represented in East Branch Brandywine Creek.

	Drainage area (sq mi)	Tons per year	Tons per year per sq mi
Watts Branch in Rockville, Md. (rural)	3.7	1,910	516
Little Falls Branch near Bethesda, Md. (urban)	4.1	9,530	3,220

Sediment production is importantly related to land slope. Using multiple correlation techniques for a large variety of data from experimental watersheds, Musgrave (1947) developed a multiple correlation in which the rate of erosion is found to be proportional to the 1.35 power of land slope and to the 0.35 power of the slope length. The same conclusion had been derived theoretically by Horton (1945) and verified by comparison with the percentage of area eroded in the Boise River basin, Idaho. Sediment yield, therefore, is more highly sensitive to land slope than to length of slope but is positively correlated with both.

Some idea, however, can be obtained of the difficulty in keeping steep slopes stable after the original vegetation has been disturbed, particularly during construction. If, for example, land slopes of 5 and 10 percent are compared, the doubling of the slope would increase the erosion rate by 2.3 times.

Increased slope length does not have such a large effect on erosion rate. Doubling slope

length would increase the erosion rate by only 22 percent.

Because a slope of 10 percent drops 10 feet in a 100-foot horizontal, temporary storage in the form of depressions which might hold silt would be nearly absent. For land slopes above 10 percent, stream channels also would tend to be nearly devoid of areas or depressions which could hold up sediment during its passage downhill. From a practical standpoint, therefore, a figure of about 10 percent probably would be a physical and economic limit beyond which construction would be especially harmful insofar as sediment production is concerned. Any such limiting slope, however, would have to be determined by detailed economic studies.

Wark and Keller (1963) related the average annual sediment discharge in the Potomac River basin to percentage of forest cover and, separately, to the percentage of land in crops. Average annual sediment yield increased from 50 to 400 tons per square mile per year, or eightfold, as forest cover in the basin declined from 80 percent to 20 percent. Sediment yield increased from 70 to 300 tons per square mile per year, or fourfold, as land in crops increased from 10 to 50 percent.

EFFECT OF INCREASED PEAK FLOWS ON SEDIMENT YIELD

It has been pointed out in the comparison of sediment rating curves for urban versus rural areas that the rating curves do not appear to be as much different as the values of sediment yield on an annual yield basis. It has been mentioned that a slight increase of sediment concentration can make a large difference in total annual sediment yield owing to the fact that urban areas produce a larger number of high flows. If the number of flows above bankfull stage is increased by urbanization, the banks and bed of a channel in erodible material will not remain stable, but the channel will enlarge through erosion. Computation indicates the seriousness of this factor.

For example, assume that a channel is capable of carrying 55 cfs at bankfull stage. In the Brandywine area this represents a channel draining a basin slightly less than 1 sq mi in area. The channel necessary to carry 55 cfs at bankfull stage would probably have a velocity of slightly less than 2.5 feet per second and would be about 2 feet deep and 11 feet wide. In figure 2, urbanization might cause a flow of this frequency to increase 2.7 times, or 150 cfs. If this channel had to adjust itself to carry a flood of 150 cfs at bankfull stage, it is estimated that the new velocity would be about 2.5 feet per second, and the necessary depth and width would have changed respectively to about 3 feet and 20 feet. In other words, this stream would deepen about 50 percent and increase in width a little less than twice its original size. If such erosion takes place through at least one-fourth mile of channel length in a drainage basin of 1 sq mi, the amount of sediment produced by this erosion would be 50,000 cubic feet. At 100 pounds per cubic foot, this amounts to 2,500 tons.

This amount can be compared with the mean annual sediment yield for Watts Branch, an unurbanized area near Rockville, Md. Annual sediment yield of Watts Branch is 516 tons per square mile. Thus, the channel erosion alone under the assumptions made would produce as much sediment as 5 years' usual production from an unurbanized area of the same size. Therefore, one can visualize that as urbanization proceeds, not only does construction activity have the potential of increasing sediment loads many thousands of times while construction is in progress, but also the result of the urbanization through its increase in peak flow would produce large amounts of sediment from channel enlargement as well. This emphasizes the need to provide temporary storage far upstream to counteract the tendency of urbanization to increase the number and size of high flows.

WATER QUALITY

There is little doubt that as urbanization increases, particularly from industrial use of land and water, the quality of water decreases. However, quantitative data to support this observation are sparse. There are two principal effects of urbanization on water quality. First, the influx of waste materials tends to increase the dissolved-solids content and decrease the dissolved-oxygen content. Second, as flood peaks increase as a result of the increased area of imperviousness and decreased lag time, less

water is available for ground-water recharge. The stream becomes flashier in that flood peaks are higher and flows during nonstorm periods are lower.

A recent study on the Passaic River at Little Falls, N.J., by Anderson and Faust (1965) provides quantitative data on the effect of urbanization and industrialization on water quality. Seventeen years of data for the flow and chemical quality of the 760-sq-mi drainage basin were analyzed. During these 17 years, diversions of water for domestic and industrial supplies increased more than 30 percent between 1950 and 1963. Returns of waste waters into the basin became as much as 10 percent of the water withdrawn. Analysis of the data showed that at relatively low discharge the dissolved-solids content increased about 10 ppm (parts per million) between 1948 and 1955 but increased 75 ppm between 1955 and 1963. That is, during the period of greatest population growth the dissolved-solids content increased nearly 40 percent in a period of 8 years.

A long-term change in the average content of dissolved oxygen was also noted. Between 1950 and 1964 the dissolved-oxygen content dropped from an average of 78 percent of saturation to 62 percent of saturation. Further, the analysis demonstrated that these average changes in water quality occurred in all seasons of the year.

An aspect of population growth not generally appreciated is the large segment of population using septic tanks for disposal of sewage. In a given area this segment often becomes large before community water and sewerage systems are built. For the planner it should be important to know how septic-tank installations can affect water quality in streams and in the ground. In the upper East Branch of Brandywine Creek, a basin of 37 sq mi, the population in 1967 was 4,200. As of that date, there were no community water or sewerage systems; all the population was served by individual wells and septic tanks. Population projections indicate that the basin will have 14,000 persons by the year 1990. During the initial part of this projected growth at least, the number of wells and septic tanks can be expected to increase materially.

The soil, containing as it does a flourishing fauna of micro-organisms, tends to destroy or adsorb pathogenic bacteria. Effluent draining from the seepage field of a septic tank tends therefore to be cleansed of its pathogens. McGauhey and Krone (1954) showed that the coliform count was reduced by three orders of magnitude in moving from an injection well a distance of 50 feet through sand and gravel. In 100 feet the count was reduced to a small number. As for rate of movement, Mallmann and Mack (1961) showed that bacteria introduced into a permeable soil by a septic-tank seepage field moved 10 feet in 2 days and 20 feet in 3 days and appeared in a well 30 feet away after 10 days.

Both the rate and effectiveness of the process of pathogen reduction depend on the type of soil as has been summarized by Olson (1964), who emphasized that position of the ground-water table is a critical factor in the transmission of pollutants.

Studies by Wayman, Page, and Robertson (1965) of the changes in primary sewage effluent through natural materials in conditions of saturated flow showed that "most soils removed over 90 percent of the bacteria from sewage within a few feet of travel * * * [but there was] severe clogging in the finer-grained soils." They found, however, that "dissolved solids moved through the columns [of soil] virtually unaffected * * *."

The same authors report on infiltration of polluted river water through sandy loam. "ABS [synthetic detergent] and coliform bacteria are significantly reduced by infiltration through the unsaturated zone; dissolved solids do not seem to be removed * * *. Once a pollutant gets into the ground water (saturated flow) little additional change in removal of ABS or dissolved solids, even for movement over extensive horizontal distances, is to be expected. This result is in agreement with the data * * * for flow of sewage effluent through various soil columns (saturated flow)."

The data are not definitive regarding the minimum distance a septic-tank seepage field should be separated from a stream channel, but the application of data cited above with

general principles does indicate some tentative rules of thumb which might be useful to the planner. A perennial stream represents the intersection of the saturated zone (water table) with the earth's surface. The observations indicate that, for soil cleansing to be effective, contaminated water must move through unsaturated soil at least 100 feet. Owing to the gentle gradient of the water table near the perennial stream and the fact that seepage water moves vertically as well as toward a nearby channel, it would seem prudent that no septic tank should be as close to a channel as about 300 feet, if protection of the stream water quality is to be achieved. The distance should probably be greater from a perennial than from an ephemeral channel. (An ephemeral stream is one which contains flowing water only in storm periods.) In general, it might be advisable to have no source of pollution such as a seepage field closer than 300 feet to a channel or watercourse.

Even this minimum setback does not prevent the dissolved materials (nitrates, phosphates, chlorides) from enriching the stream water and thus potentially encouraging the proliferation of algae and otherwise creating a biotic imbalance.

The only detailed study of the effect of urbanization on water temperature is that of E. J. Pluhowski (1968), some of whose results are summarized here. He chose five streams on Long Island for detailed analysis and found that streams most affected by man's activities exhibit temperatures in summer from 10° to 15°F above those in an unurbanized control. Connetquot River, the control stream, flows through one of the few remaining undeveloped areas of central Long Island. Temperatures in reaches most affected by ponding, realinement, or clear cutting of trees are significantly higher in summer, but winter temperatures are 5° to 10°F colder than those observed in reaches unaffected by man.

Solar radiation is the predominant factor in the energy balance determining a stream's thermal pattern. The more solar energy a stream absorbs, the greater its temperature variation diurnally as well as seasonally. By greatly increasing the surface area exposed to the sun's radiation, the construction of ponds and lakes has profoundly affected stream temperature regimen. On Long Island, Pluhowski found that ponds having mean depth of about 2 feet or less substantially increase downstream diurnal temperature fluctuations whereas ponds deeper than 2 feet exhibit a dampening effect on daily temperatures. For example, during the period October 31 to November 2, 1967, the mean daily range of temperatures at Swan River, in south-central Long Island, varied from 9°F in a reach immediately below a shallow pond (mean depth, 0.5 foot) to 3°F below Swan Lake (mean depth, 3 feet). In reaches unaffected by man's activities, the mean daily temperature fluctuation was about 4°F.

Under natural conditions, less than 5 percent of the streamflow on Long Island originates as direct surface runoff. With the conversion of large areas of western Long Island from farmland to suburban use during the last 20 years, the proportion of streamflow originating as surface runoff has increased sharply. As a direct consequence, streams most affected by street runoff may exhibit temperature patterns that are markedly different from those observed in streams flowing through natural settings. During the period August 25 to 27, 1967, a series of heavy rainstorms overspread Long Island. Throughout this period, temperatures at each of the five observation sites on Connetquot River showed little day-to-day change. In contrast, temperatures in the upper reaches of East Meadow Brook, which drains highly urbanized central Nassau County, increased steadily in response to the relatively warm street runoff. Pluhowski found that by August 27, water temperatures had risen 10° to 12°F above prestorm levels and were 15°F higher than concurrent temperatures in the control stream.

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