Stream Channel Enlargement Due to Urbanization

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Abstract. Stream channel enlargement occurs in response to the change in streamflow regimen accompanying urbanization. This empirical study relates the imputed increase in channel cross-sectional area to detailed land use data and other information for 78 small watersheds near Philadelphia. Important differences between the effects of various types of impervious land use are observed: large channel enlargement effects are found for sewered streets and area of impervious parcels such as parking lots, and much smaller effects are observed for unsewered streets and impervious area involving detached houses. Relatively low channel enlargement effects are attributed to all types of impervious development less than 40 years old and also to street and house area more than 30 years old. The influence of impervious development on channel size is found to be significantly related to topographic characteristics of the watershed, to the location of impervious development within the watershed, and to man-made drainage alterations. Although the relative importance of these interactive factors proves difficult to establish, the most critical determinant of the amount of channel enlargement resulting from a given level of urbanization appears to be bank slope.

It has been widely recognized that urban development in a watershed causes change in streamflow regimen [Anderson, 1988; Leopold, 1968]. The process of urbanization tends to increase the peak flow magnitudes through the spread of impervious area, which increases the volume of runoff, and through drainage alterations (such as storm sewerage), which facilitate the movement of runoff through the basin. The study reported here has focused on a phenomenon that accompanies the increase in peak flows, namely, the enlargement of stream channels due to urbanization.

Observers in the past have suggested that stream channels tend to maintain a state of quasiequilibrium with the flow regimen of the stream such that there is a constant frequency of overbank flow. This frequency has been estimated at approximately 1.5 years [Leopold, 1964]. For watersheds affected by urbanization, Leopold [1968] has hypothesized that stream channels tend to enlarge by an amount sufficient to maintain a similar quasiequilibrium state under the altered flow regimen; thus the amount of channel enlargement would be roughly proportional to the increase in the 1.5-year flood. Although recent findings have caused the common bank-full frequency hypothesis to be seriously questioned [Kilpatrick and Barnes, 1964], the notion that stream channels respond to urbanization by enlarging in roughly the same proportion as the increase in peak flows does appear intuitively plausible.

Channel enlargement resulting from urbanization has been considered an important subject of investigation for two reasons. First, the process of channel enlargement itself involves a serious reduction in the aesthetic and recreational value of the stream and incurs monetary costs in many instances. For small streams this effect must be considered one of the major negative impacts of urbanization on stream quality. Second, a more detailed treatment of urbanization is possible when studying channel enlargement than when studying peak flow increase, since in the former case it is not necessary to rely on stream gage data and hence a larger sample of streams can be employed. This circumstance has allowed the present study to consider empirically a wide variety of factors relevant to the hydrologic impact of urbanization.

CHANNEL MEASUREMENT PROGRAM

The study has involved 78 watersheds 1-6 mi² in area in the Pennsylvania portion of the
Urbanization Effects

The change in streamflow, the impeded increase in information for 78 small watersheds of various types of streams are found for sewerage and much smaller effects in the Piedmont physiographic area. Fifty of the sample watersheds contained some degree of urbanization in the form of large-scale residential, commercial, or industrial development; 28 watersheds contained only rural land uses.

The channel measurement process consisted of stretching a tape across the stream so that it was level and perpendicular to the channel and measuring the vertical distance between the tape and the earth surface at 2-foot intervals. The depth of the channel at each point was computed by subtracting from each measurement the vertical distance between the tape and the point chosen as the bank top. These data were then used to compute the overall channel width, depth, and cross-sectional area for each cross section. (The computation of width and depth was based on the use of a computer program to find the best fitting rectangular approximation to the channel cross section.)

It was found early in the study that the channels of many small streams are quite irregular and show considerable variation in cross-sectional area; this irregularity is particularly true for streams that drained urbanizing areas. For such streams it was obvious that only at a limited number of channel points could the channel be in quasiequilibrium with the flow regimen of the stream. Because of this finding no attempt was made to obtain measurements that would provide a complete characterization of the channel within a chosen reach. Rather, measurements were made only at points of apparent quasiequilibrium with streamflow.

Elaborate criteria for identifying quasiequilibrium channel points were developed as part of the study. These criteria are described in detail elsewhere [Hammer, 1971a]. The most important feature of these points is that the lower bank, the elevation of which defines the bank ‘top’ when computing channel dimensions, consists of a berm or bank segment that has been recently constructed by the stream, i.e., by deposition of sediment. The most commonly recognized situation in which such bank segments are found is that described in the familiar meander model of channel behavior, which specifies that a meandering stream will erode its bank at the outside of a bend and will build a succession of new bank segments at the inside and thus a ‘floodplain’ will be constructed within the bend. An equally common situation found in the present study, however, was the existence of recently built bank segments at points where the channel had apparently become overwiden through scouring.

Four or more cross-sectional measurements were executed for most of the streams. The two variables of interest computed from these data were the channel cross-sectional area and the ratio of channel width to depth. The latter variable was formulated to test the possibility that channel enlargement due to urbanization typically involves a greater proportionate increase in channel width than in channel depth or vice versa. In preliminary studies the width to depth ratio was found to be correlated with channel slope and watershed area but showed no significant relationship to the degree of urbanization or to the apparent increase in cross-sectional area caused by urbanization.

Thus the remainder of the analysis was concerned only with channel cross-sectional area, expressed as an average for each stream.

LAND USE AND OTHER WATERSHED DATA

The collection of watershed data involved the use of a grid system for each watershed, the grid squares being 40 acres in size. Thirty variables pertaining to land use and topographic characteristics were measured and recorded for each grid square. Each topographic variable (e.g., land slope) was measured as an average for land in the square. The grid square size of 40 acres was recognized to be inappropriately large for the consideration of factors such as land slope, since a great deal of variation can occur within such an area. A smaller size would have resulted in an infeasible number of grid squares to be considered however.

The set of land use measurements consisted of an exhaustive partitioning of the land area in each grid square into 17 categories. These measurements were executed by using aerial photographs (1 inch = 400 feet) and an intensive field survey of the sample watersheds.

The major focus of attention was land in impervious uses. Three basic categories of impervious area were considered: streets and sidewalks, houses and related impervious area, and...
all other impervious area. The first of these categories included the area of all paved streets, highways, rural roads, and expressways plus the area of paved sidewalks. The second included all impervious area associated with single-family (or two-family) houses, namely, the houses themselves; paved driveways, walks, and patios; and outbuildings, such as garages, sheds, and small barns. (These two categories will henceforth simply be referred to as 'area of streets' and 'area of houses.' The category of 'other' impervious area included a wide variety of land uses: commercial buildings, apartment houses, factories, airport runways, shopping centers, row houses, and especially parking lots. Approximately two thirds of the land in this category consisted of paved area instead of structures.

Within the 78 sample watersheds these three categories of impervious surface accounted for approximately equal portions of the total impervious area. Measurement of these variables was greatly facilitated by the fact that most of the impervious development in the sample watersheds was suburban and fairly recently constructed. Thus there was great uniformity in street width and in house types, and also most of the other impervious area occurred in large parcels, e.g., shopping centers.

The length of time that impervious development had been in existence was expected to be important to channel enlargement. Therefore the impervious area in each of the three groups was subdivided into three age categories: area less than 4 years old, area 4-15 years old, and area greater than 15 years old. (This division was made possible by the fact that the aerial photographs were 4 years out of date and the topographic maps were approximately 15 years out of date at the time of the study.) Later in the study a fourth age category was created, applying only to street and house area; this category was the development constructed prior to 1940, as was estimated by using aerial photographs and the U.S. Census of Housing.

Another aspect of impervious development considered important was the existence of street storm sewerage. Although an exact determination of which street segments were underlain by storm sewers was not feasible, it was observed that the existence of curbing (usually associated with sidewalks) usually implied the existence of storm sewers and vice versa. Thus the procedure adopted was to consider any street segment with continuous curbing to be sewered. By using this definition, estimates were prepared for each grid square of the area of sewered streets and the area of houses fronting on sewered streets in each of the various age categories.

The major nonimpervious land uses considered were nonimpervious developed land, wooded land, land in cultivation, and 'open land.' The nonimpervious developed land category consisted primarily of lawn area; it was obtained for each grid square by subtracting the area rendered impervious from the overall area of land in intensive nonagricultural use. Open land was obtained as an overall residual by subtracting from total land area the amount of wooded land, land in cultivation, and land in intensive nonagricultural use. Land in this category consisted largely of pasture and unsigned grassland.

The topographic and drainage system factors measured for each grid square were the average land slope, the length and average slope of the flow path from the grid square to the point which the flow reached the stream channel, the length and slope profile of the stream channel from the point just mentioned to the watershed mouth, and the extent of man-made alteration to these drainage path components. With regard to drainage alterations, any portion of the drainage path from the grid square to the watershed mouth would be considered altered if that portion consisted of a smooth artificial channel (e.g., a pipe) the cross-sectional area of which was at least as large as the probable area of the natural channel that it replaced. A number of variables in addition to those given above were considered, including several uses of land; some of these are mentioned below.

FORM OF THE REGRESSION ANALYSIS

The dependent variable in the regression analysis was a quantity involving channel cross-sectional area; this quantity was termed the 'channel enlargement ratio.' This variable incorporated an empirical relationship between channel cross-sectional area and watershed size for unurbanized basins. The relationship was estimated by using the 28 rural watersheds in the sample, was the following (with a constant equal to

\[ \log C = 1 - 2.68 \]

where \( C \) is the ratio of runoff to precipitation in a 20-year flood.
form sewers and vice versa. This adopted was to consider any with continuous curbing being defined, estimates were each grid square of the area and the area of houses fronting each of the various age nonimpervious land uses consisting impervious developed land in cultivation, and open land nonimpervious developed land category of lawn area; it was a grid square by subtracting the impervious from the overall area sensitive nonagricultural use. Opened as an overall residual by subtracting total land area the amount of land in cultivation and land agricultural use. Land in this category largely of pasture and unused.

The drainage system factor, each grid square were the average length and average slope of the grid square to the point at which the stream channel, the profile of the stream channel just mentioned to the watershed extent of man-made alteration path components. With grade alterations, any portion of the grid square to the mouth would be considered altered consisted of a smooth artificial pipe) the cross-sectional area at least as large as the probable rural channel that it replaced. Variables in addition to those considered, including several measures of these are mentioned below.

THE REGRESSION ANALYSIS

The dependent variable in the regression quantity involving channel element ratio. This variable an empirical relationship between sectional area and watershed basins. The relationship, the 28 rural watersheds in the following (with a correlation coefficient equal to 0.87):

\[
\log C = 1.3945 + 0.6573 \log A
\]

where \(C\) is the channel cross-sectional area in square feet and \(A\) is the watershed area in square miles.

The channel enlargement ratio \(R\) was computed as follows for each of the 78 sample watersheds:

\[
R = \frac{C}{24.8A^{0.657}}
\]

The channel enlargement ratio consisted of the channel cross-sectional area of each stream as a proportion of the expected channel area in the absence of urbanization; thus the ratio expressed the amount by which channel size was augmented to have increased because of urbanization. (Whereas the subject streams were observed only once instead of over a period of time, the use of the term channel enlargement ratio is justified only by the fact that the ratio was indeed found to be strongly related to urbanization. This finding indicates that the channels of the urbanized streams had in fact enlarged relative to their preurbanization size.)

Values of the enlargement ratio in the sample ranged from 0.7 to 3.8, the majority lying between 1.0 and 2.0.

The basic set of independent variables used to explain the channel enlargement ratio consisted of the proportions of the watershed area devoted to various land uses. In addition, a large number of interaction variables were formulated to investigate the possible influence of topographic and other factors on the effects produced by impervious land uses. An interaction variable was prepared by multiplying, for each individual grid square, a land use measurement times some other characteristic of the grid square, e.g., average land slope; the resulting figure was summed over all the grid squares and was divided by the watershed area.

Many of the grid square characteristics incorporated in the interaction variables were factors that were not relevant to the amount of runoff yielded by the grid square itself but that might affect the contribution of its runoff to peak flows at the watershed outlet. An example of such a factor is the distance of flow from the grid square to the stream channel. In dealing with factors of this nature the following assumption was made: the relative importance of the various impervious land uses to channel enlargement when they are weighted by such a factor should be the same as their relative importance in unweighted form. This assumption led to the use of a single interaction variable for each factor, in which the factor was multiplied by a linear combination of impervious land uses for each grid square instead of by an individual land use. The coefficients in this linear combination were intended to equal the respective regression coefficients of the impervious land uses in unweighted form. This equality of coefficients was achieved by iterating the regression.

Two independent variables not involving land uses were included in the final regressions. One of these was a watershed shape index measuring the deviation of the watershed from circularity. This variable was the moment of the watershed about its center of mass (as a two-dimensional figure) divided by the moment of a circle having the same area. The other variable was a soil drainage index based on the USDA Soil Survey classification of soils as being 'well-drained,' 'moderately well-drained,' 'somewhat poorly drained,' or 'poorly drained.' Arbitrary scores of 4, 3, 2, and 1 were assigned to these soil descriptions, respectively, and the average score for soils in each watershed was computed. These two variables were both consistently strong in explaining the channel enlargement ratio.

REGRESSION RESULTS

Four different sets of regression results were obtained as the final outcome of the data analysis. These regressions differed with regard to the grouping of impervious land uses, the treatment of age categories of impervious area, and the formulation of interaction variables. Only one set of regression results is reported here in full; this regression involved the least complex group of independent variables. The other regression results are described somewhat less formally in the following interpretive sections.

The regression reported here contains only one interaction variable, which deals with the average slope of the flow path from a given grid square to the watershed outlet. This
average slope, expressed as a percent, was multiplied by the following linear combination of impervious land uses for each grid square:

\[ 0.83 X_1 + 3.25 X_2 + 3.79 X_3 \]

where \( X_1, X_2, \) and \( X_3 \) denote the area of houses, the area of streets, and the area of other impervious land, respectively. The results of this regression are presented in Table 1.

The two variables not involving land uses were entered in the form of deviations around their means. Thus note that the constant term in the regression represents an estimate of the mean slope for the area of houses, area of streets, and area of other impervious land.

Each of the regression coefficients for independent variables dealing with land use represents the difference between the channel enlargement effect for the given use and the area of open land. Thus the channel enlargement effect, for example, would be 0.60 + 0.129 = 1.29. For the major impervious land use, the channel enlargement effects include interaction with slope of flow. To calculate typical values of these quantities, the following relationship was estimated for watersheds in our sample: \( 1.874^{0.89} \).

This value is similar to those obtained for the 100% sewerage watershed. For the hypothetical watershed in each of the various land uses, the channel enlargement ratio of approximate 10% impervious area was considered by Leopold to be consistent with the results of other studies. The value 1.874 was not considered by Leopold to be consistent with the results of other studies.

The values listed in Table 2 would be multiplied by the proportions of watershed devoted to various uses to yield an estimate of the channel enlargement ratio in any particular situation. For example, an urbanized 1-m² basin might have 70% of its area in nonimpervious developed land and 10% in houses fronting on sewered streets and 10% in other impervious area; the expected channel enlargement ratio in this case would be \( 0.7(1.08) + 0.1(2.19) + 0.1(5.95) + 0.1(1.00) = 2.25 \).

General evaluation of results. In consideration of the overall levels of effect predicted by the results, it is useful to compare them with findings of earlier studies investigating the effects of urbanization on peak flows. Leopold [19] has summarized the results of a number of studies. He focused on the ratio of average annual flood after urbanization to average annual flood before urbanization for a 1-m² watershed. This ratio is related to tabular and general form to two urbanization variables, the percent of watershed area rendered impervious and percent of severed watershed area.

The values described by Leopold for the average annual flood ratio are quite similar to the values indicated by this study for the channel enlargement ratio. For example, the estimated average annual flood ratio of a 100% impervious watershed is 108, which is consistent with the results of Leopold's study.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Regression Coefficient</th>
<th>Standard Error of Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land in cultivation</td>
<td>0.3896</td>
<td>0.1291</td>
</tr>
<tr>
<td>Wooded land</td>
<td>-0.1518</td>
<td>0.1151</td>
</tr>
<tr>
<td>Land in golf courses</td>
<td>1.6416</td>
<td>0.5338</td>
</tr>
<tr>
<td>Area of houses &gt; 4 years old fronting on sewered streets</td>
<td>0.8291</td>
<td>0.7462</td>
</tr>
<tr>
<td>Area of sewered streets &gt; 4 years old</td>
<td>3.2499</td>
<td>0.8988</td>
</tr>
<tr>
<td>Other impervious area &gt; 4 years old</td>
<td>3.7855</td>
<td>0.4486</td>
</tr>
<tr>
<td>Nonimpervious developed land plus impervious area &lt; 4 years old and unsewered streets and houses</td>
<td>0.1870</td>
<td>0.0890</td>
</tr>
<tr>
<td>Interaction variable: average slope of flow path to watershed mouth</td>
<td>0.2966</td>
<td>0.0350</td>
</tr>
<tr>
<td>Watershed shape index</td>
<td>-0.1900</td>
<td>0.0776</td>
</tr>
<tr>
<td>Soil drainage index</td>
<td>-0.1072</td>
<td>0.0247</td>
</tr>
<tr>
<td>Constant term</td>
<td>0.9025</td>
<td></td>
</tr>
</tbody>
</table>

Multiple \( R^2 = 0.9813 \).
Urbanization Effects

TABLE 2. Channel Enlargement Effects of Land Uses in a 1-Square-Mile Basin—Version 1

<table>
<thead>
<tr>
<th>Land use category</th>
<th>Effect (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land in cultivation</td>
<td>1.29</td>
</tr>
<tr>
<td>Wooded land</td>
<td>0.75</td>
</tr>
<tr>
<td>Land in golf courses</td>
<td>2.54</td>
</tr>
<tr>
<td>Area of houses &gt; 4 years old on fronting streets</td>
<td>2.19</td>
</tr>
<tr>
<td>Area of streets &gt; 4 years old</td>
<td>5.96</td>
</tr>
<tr>
<td>Other impervious area &gt; 4 years old</td>
<td>6.79</td>
</tr>
<tr>
<td>Nonimpervious developed land plus</td>
<td>1.08</td>
</tr>
<tr>
<td>impervious area &lt; 4 years old and</td>
<td></td>
</tr>
<tr>
<td>unsealed streets and houses</td>
<td></td>
</tr>
<tr>
<td>Open land (residual category)</td>
<td>0.90</td>
</tr>
</tbody>
</table>

have a negative influence. This pattern was observed in all regression results, including regressions that involved only the 28 rural streams. The coefficient for land in forest was not significantly different from 0 at the 5% level in the regression reported above; but this variable was retained because of its statistical significance in other regressions and because of the stability of its estimated effect throughout the analysis. (A similar situation prevailed for areas of houses fronting on unsealed streets.)

Quite a large regression coefficient was obtained for land in golf courses. This land use was expected to have a greater impact on channel size than most nonimpervious land uses, owing to its drainage characteristics and to the watering of fairways during summer months.

Nonimpervious developed land was an important land use in the sample watersheds, accounting for more than 20% of the total land area surveyed. A small but significant positive coefficient was obtained for this land use both when it was combined with impervious area categories (unsealed streets and houses and impervious area less than 4 years old) and when it was entered singly. The positive coefficient was not unexpected, since the developed land category contained a variety of land uses besides residential lawn area. This category included some land in intense use (such as unpaved parking areas) and much land immediately bordering sewered impervious surfaces (such as highway medians and land between streets and sidewalks). The estimated effect for this use must be viewed only as an overall average for developed land not actually rendered impervious; the possibility remains that the effect of established lawn area per se might be less than that of open land.
Types of impervious area. The largest effect on channel enlargement was estimated for other impervious area. Area of sewered streets was next and was followed by area of houses fronting on sewered streets. This pattern was maintained in all regressions, although the relative sizes of estimated effects did vary considerably (see Table 2 versus Table 3).

It was hypothesized that the great influence attributed to other impervious area and the relatively small importance attributed to houses had to do with the size of impervious parcels involved. Parking lots and large buildings might yield storm runoff in such quantities that the proportion lost to infiltration or depression storage during flow to the stream would be minimal, whereas this proportion might be large for runoff from houses, driveways, patios, and so on. A partial test of this hypothesis was conducted by giving separate consideration to other impervious area found in parcels greater than 5 acres in size (which accounted for approximately half the total); but the regression coefficient for this subcategory did not differ significantly from the coefficient for the remaining other impervious area.

The large effect estimated for other impervious area is striking in view of the fact that this effect holds without regard to drainage facilities present. (Drainage facilities specifically serving these areas were not surveyed in the study.) To test for the possible importance of proximity to sewered streets, a variable was formed in which other impervious area was weighted by the density of sewered streets for each grid square. No importance was attributed to this variable in the regression however.

Low effects were obtained throughout the analysis for area of unsewered streets and houses fronting on unsewered streets. As was indicated earlier, it is believed that the importance of street sewerage to the effects produced by street and house area was somewhat exaggerated. One suspected reason for this exaggeration is the existence of a negative correlation among urbanized watersheds between the proportion of streets that are unsewered and the efficiency of the drainage facilities for streets that are sewered. This correlation would lead to a downward bias in the regression coefficient for unsewered streets and an upward bias, relative to average conditions, in the coefficient for sewered streets (and similarly for houses). A second reason is the probable existence of correlations between the proportion of unsewered streets and various characteristics of the surrounding nonimpervious land. (See the discussion of age of impervious area below.)

In one version of the regression the area of streets in residential districts with detached houses was added to the area of houses to form a single ‘residential impervious area’ category. Two variables relating to this category were entered in the regression, i.e., sewered residential impervious area and all residential impervious area weighted by average land slope, as a percent, for each grid square. The coefficients obtained for these variables were, respectively, 2.02 and 0.18 (see equation 3). Although the importance attributed to land slope may be questionable, the channel enlargement effects thus yielded for sewered versus unsewered area are probably more reasonable than those obtained in other formulations. For residential impervious area located in a 1-m³ basin on land with a slope of 5%, the estimated channel enlargement effects would be approximately 4.2 for sewered area and 2.0 for unsewered area; if land slope was 10% the effects would be 5.2 and 3.0.

A special category of houses, not heretofore mentioned, was given separate treatment in the study. This category included houses having direct, underground connections between gutter downspouts and the storm sewerage system. This sort of construction was found only in the city of Philadelphia, where these connections are required by building code. The estimated channel enlargement effect of houses possessing this feature was consistently very high and similar to the effect of other impervious area. Thus in the final runs of the regression this land use was included with other impervious area.

Age of impervious area. The length of time that impervious development had been in existence was important in the study in two different ways. First, since stream channel enlargement must require some length of time to be accomplished, one would expect that the observable effect of a parcel of impervious area on the stream channel at a given time would be positively related to the age of the parcel at that time. Second, the results of the study have suggested that relative age of impervious area on the stream is the same for all types of structures. The importance of age was similar for all types of construction. Further, the same percent was the time element for both categories. To control for the number of parameters necessary to estimate the influence of impervious area and age categories. The assumption that a linear relationship is all that is necessary to be an estimate of the influence of impervious area and age categories. The assumption that a linear relationship is all that is necessary to be an estimate of the influence of impervious area and age categories. The assumption that a linear relationship is all that is necessary to be an estimate of the influence of impervious area and age categories. The assumption that a linear relationship is all that is necessary to be an estimate of the influence of impervious area and age categories. The assumption that a linear relationship is all that is necessary to be an estimate of the influence of impervious area and age categories.
and similarly for houses). In the probable existence of urban areas, the proportion of unsewered land characteristics of the service land. (See the discussion area below.)

of the regression the area of initial districts with detached to the area of houses to form impervious area category. dating to this category was a regression, i.e., sewered residential area and all residential heighted by average land slopes each grid square. The co for these variables were, respectively, 0.18 (see equation 3) and 0.18 (see equation 3) for impervious area. The estimated channel rise for Sewered versus yield for impervious area would probably more reasonable in other formulations. For various area located in a 1-nil slope of 5%, the estimated effects would be approximately area and 2.0 for uninhabited slope were 10%, the effects 3.

new of houses, not heretofore separate treatment in the formerly included houses having connections between gutter and storm sewerage system. Action was found only in the area, where these connections ailing codes. The estimated effect of houses possessing consistently very high and as of other impervious area, the runs of the regression this area with other impervious.

area. The length of time development had been in existence in the study in two different stream channel enlargement length of time to be accomplished expect the observable impervious area on the time of the parcel at that time. The results of the study have suggested that relatively old impervious area, in existence more than 30 years, may have less effect on the stream channel than development constructed somewhat more recently.

With regard to the first of these considerations, an assumption was made that the relative importance of age of development should be the same for all types of impervious area for example, if the influence of street area 4-15 years old is only 75% as great as the influence of street area more than 15 years old, owing to the time element in channel enlargement, then the same percentage should apply to house area and to other impervious area in these two age categories. The incorporation of this assumption in the analysis reduced the number of parameters to be estimated and made it necessary to iterate the regression, i.e., to estimate the influences associated with type of impervious area and age of impervious area in successive rounds.

In the initial phase of analysis (before separate consideration was given to impervious development more than 30 years old) the following results were obtained for the various age categories. Impervious area less than 4 years old was found to have no positive influence relative to open land, but impervious area 4-15 years old was attributed an influence fully as large as that of development more than 15 years old. In response to these results, area 4-15 years old and area more than 15 years old were simply added together for each impervious area type, and impervious area less than 4 years old was deleted from the regression as a separate factor. This action yielded results such as those shown earlier.

It was observed in the analysis that watersheds with relatively old development tended to have relatively low values of the channel enlargement ratio. Thus separate consideration was given to area of sewered streets and area of houses fronting on sewered streets that had been in existence for more than 30 years at the time of the study, i.e., were built before 1940. The result was that notably lower effects were estimated for area more than 30 years old than for area 15-30 years old, especially in the case of house area. The level of statistical significance that can be attached to the addition of a separate 30-year category is indicated by the fact that in regressions for which this step simply involved adding one independent variable the variable would be found significant at the 5% level but not at the 1% level.)

A likely explanation for this finding is that the drainage facilities serving older residential areas might tend to be relatively poor, either because they were underdesigned to begin with or because they have deteriorated over time. It is probable that an equally important cause, however, was the association between age of development and characteristics of the land not rendered impervious. Older residential developments tend to have more trees, shrubbery, and other dense vegetation than newer developments; also the soil structure itself has had more time to recover from being disturbed (if indeed it was ever disturbed). The negative influence of these factors on runoff and stream channel enlargement would, in the absence of other relevant variables, be attributed to the age of impervious area.

Regardless of which explanation is more important, it is difficult to say whether the relatively low effects estimated for older impervious area should be interpreted to mean that the impact of any residential development should be expected to decrease eventually or whether the low effects pertain only to development of a certain type that was built primarily before 1940.

When streets and houses more than 30 years old were given separate consideration in the regression, the estimated influence of impervious area 4-15 years old and area 15-30 years old differed appreciably. Also positive regression coefficients were obtained for impervious area less than 4 years old, although these were never statistically significant. The channel enlargement effects estimated in this case are shown in Table 3.

Influences of natural watershed features. One of the principal aims of the study was to state the importance of watershed features and the location of development within a watershed in such a fashion that the channel enlargement effects of development in different watersheds or at different points in given watershed might be compared. The desire to obtain results that would be usable for intrawatershed comparisons made it necessary to consider topographic factors pertaining to individual grid squares instead of overall basin indices. Also the inter-
TABLE 3. Channel Enlargement Effects of Impervious Land Uses in a 1-Square-Mile Basin—Version 2

| Impervious area  <4 years old and unsewered street and house area | 1.08 |
| Area of houses fronting on sewered streets | |
| Houses 4–15 years old | 3.36 |
| Houses 15–30 years old* | 4.15 |
| Houses >30 years old† | 1.08 |
| Area of sewered streets | |
| Streets 4–15 years old | 4.20 |
| Streets 15–30 years old* | 5.16 |
| Streets >30 years old† | 3.76 |
| Other impervious area | |
| Area 4–15 years old | 6.26 |
| Area >15 years old | 7.99 |

* Built after 1940.
† Built before 1940.

Watercourses (as defined earlier) would not involve any reduction in impact. These assumptions are of course naive in view of the complexities of basin hydrology.

Flow to channel and flow in channel were treated in two separate variables, each of which involved distance divided by a function of slope (for individual grid squares). The quantity used to weight impervious development in the final form of the flow to channel variable consisted of the flow distance to the stream channel divided by the square of the average slope of this flow path. The flow in channel variable was based on measurements of the length, slope, and drainage area of a series of separate channel intervals. The quantity used to weight impervious development in this variable consisted of a summation, over all channel intervals relevant to a given grid square, of the interval length divided by a slope index pertaining to the interval (see equation 3 below).

The influence of watershed size was intended to be expressed by way of a third variable involving only watershed area \( A \) raised to some exponent. Therefore steps were taken to remove the association with watershed size from the flow to channel and flow in channel variables. Both these variables were divided by the quantity 0.9854\( A^{-0.1} \), which represented an estimate (based on the current sample) of the average flow distance in miles from all points in a watershed to the watershed mouth. In addition, the slope index used in the flow in channel variable incorporated an adjustment for the association between channel slope and drainage area. This the influence of watershed size was effectively isolated in the watershed size variable. The form of this variable that worked best was an exponential type equation estimated using the known watershed area, average land slope, and channel length parameters.

The concentration of population in the channel is determined by the natural drainage pattern and the expected channel discharge. For a watershed of the type in question, the channel slope is lower per se than that expected in natural channels. The influence attributed to watershed size is somewhat smaller than that expected according to the exponential function. The size effect is a less than a square-root function of the impervious area.

The equation estimated in this phase of the analysis (the variables not relating to impervious development being omitted) is presented in (3). In this equation the impervious development in each grid square is multiplied by a term that could vary from 1.3 (for a development located at the mouth of a 1-mi² watershed) down to very small or even negative values depending on the size of the channel and the slope.

Within the sample watersheds studied, however, the variation in this term was generally moderate.

The influence attributed to watershed size is somewhat smaller than that expected according to the exponential function. The size effect is a less than a square-root function of the impervious area.
sion was fully as great as that in the form just discussed. The ability of the overall slope of flow variable to substitute for variables expressing watershed size, flow to channel, flow in channel, and land slope was due to the high levels of intercorrelation between these variables. The fact that the substitution was possible reflects negatively on the probable accuracy of the coefficients shown in (3).

Use of the equation involving the overall slope of flow variable to compare the influence of impervious development at different locations in a watershed could lead to erroneous conclusions. For example, because the typical upward concavity of watercourses, the average slope of flow to the watershed mouth is likely to increase with distance of flow; but the influence of impervious development presumably decreases with distance of flow. Thus the overall slope of flow factor must be considered in the nature of an overall basin index, which is suitable only for comparing the average effects of development in different watersheds.

SUMMARY AND CONCLUSIONS

The study has indicated that important differences exist between the channel enlargement effects of different impervious land uses. The effect of impervious area associated with detached houses is small unless the gutter downspouts connect directly with storm sewers. The effect of street and sidewalk area is large if the streets are severed but is small otherwise. Other impervious areas, which consist primarily of contiguous impervious surfaces exceeding 1 acre in size, has a very large channel enlargement effect. Influence on channel size increases with the length of time that impervious development has been in existence, as is expected, but relatively low effects are observed for street and house areas, more than 30 years old. The latter fact may or may not indicate that the impact of residential development tends to decrease eventually.

The impact of impervious development appears to be positively related to channel slope, slope of flow to channel, and slope of the developed land itself (in the case of residential areas). It is negatively related to the distance of flow to channel and flow in channel, excepting portions of the flow path that have been altered by man. The channel enlargement ratio associated with a given intensity of development also bears a mild negative relationship to watershed size. Although the relative importance of the various topographic and drainage system characteristics is difficult to establish, the slope factors appear to be more influential than distance factors (which involve location of development within the watershed). Man-made alterations to the drainage system other than sewerage of the impervious area itself are attributed a milder influence than that expected.

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