GEOMORPHIC EFFECTS OF URBANIZATION IN FORTY-ONE YEARS OF OBSERVATION

by

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AT THE 1899 meeting of the Geological Section of the British Association for the Advancement of Science, the presidential address was delivered by the eminent geologist Sir Archibald Geike. His paper (1905) was entitled "Geological Time." He noted with some alarm the widely differing views among geologists, paleontologists, and the new physicists as to the length of geologic time, the rates of erosion, and the gradual increase in complexity of organisms. He was particularly concerned about the rates of geological processes. Geike expounded on the various interpretations of uniformitarianism and concluded with a plea for direct measurement as an antidote for speculation.

> We cannot but be struck with the predominant vagueness . . . and general absence of such numerical data determined by accurate, systematic, and prolonged measurement as would alone furnish a satisfactory basis for computation of the rate at which denudation takes place.
>
> Some instrumental observations of the greatest value have indeed been made, but for the most part, observations of this kind have been too meager and desultory.
>
> We need not at first be too ambitious. The simplest, easiest, and least costly series of observations might be chosen for a beginning. (P. 232)

PROGRAMS OF REPETITIVE OBSERVATIONS

Though these words of our predecessor were not known to him at the time, the senior author began in 1953 a modest observational program

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on a small drainage basin in Maryland, for the purpose of obtaining information on processes, their rates, and their cumulative effects. The program, as it turned out, quite fitted the recommendations of Sir Archibald, being simple, not costly, quantitative, and long continued. Interestingly, repetitive observations extending as long as one or several generations occur primarily in hydrology and climatology. Examples are the rainfall record at Santa Fe, New Mexico, that began in 1846; the long temperature record at New Haven, Connecticut; the streamflow station at Embudo, New Mexico, that began in 1895; and the thousand-year record of the gage height of the Nile. In geophysical processes, the most famous is the record of carbon dioxide in the atmosphere taken at Mauna Kea.

Recording the occurrence of past events is highly important; examples include the dates of great floods, earthquakes, and several types of astronomical observations. Discovering changes in conditions by interpretation of stratigraphy, glacial cores, varves, and pollen is the substance of a wide variety of geologic, geophysical, and paleontologic specialties. But direct observation of geomorphic process through time by repetitive or continuous measurement is still uncommon. Its importance has recently been enhanced by the changes in rates caused by anthropogenic effects that now assume great importance with the emergence of environmental concerns.

There is a qualitative difference between recording the day-to-day or annual value of such parameters as temperature or streamflow, and the establishment of permanent benchmarks from which measurements at some time in the future will permit the evaluation of change that has occurred in the intervening time. Monumented benchmarks from which a survey may be repeated are a gift to the future. They may allow future scientists to learn something specific about types and rates of change that takes place over intervals of more than a generation. As described by Ernest Partridge and his several coauthors, the ethos of transcendence beyond oneself in the interest of those who follow enriches our own life. He says that "we owe it to ourselves to be duty-bound to posterity, in a manner that genuinely focuses on future needs rather than our own" (Partridge 1981, 218). Earth scientists and geomorphologists in particular might embrace this simple expense of effort.

Requirements for a Useful Program

During his professional lifetime, the senior author saw a series of events in which measurements were made with the hope and expectation that they would be repeated in the future. But in each instance re-measurement was precluded because of loss of records or loss of the field benchmarks.

These losses of interesting and useful data demonstrated that three requirements must be fulfilled if any program of observation through time is to be successful:

1. The field sites must be marked or monumented, or so well known that the exact location can be found and its principal characteristics, say, elevation, can be reestablished.
2. The measurements must be repeated in comparable manner at the same order of precision, and recorded in a consistent way so that a later observer is assured of comparable results.
3. The field notes must be preserved from loss by neglect, fire, or failure to find them. Though publication of the data is a partial insurance, it generally does not convey all the information that might be found in the originals. Duplication of the originals so that two copies are stored separately is an approach to this objective.

The Programs of Observation

In the light of this experience and in concert with a basic purpose of the Water Resources Division of the U.S. Geological Survey, Leopold initiated three programs of repetitive observations in response to the perceived need for improved knowledge of geomorphic and hydrologic changes through time. The present paper presents some details of the first of these programs, but a principal objective of the present paper is to emphasize the larger problem that Sir Archibald discussed a hundred years ago.

The second program was a network of benchmark gaging stations (Leopold 1962b). The sites were chosen to represent areas essentially uninfluenced by man or his works. They are located in national parks, monuments, and forests distributed through the whole United States. Most of the fifty-odd now in operation were established in the 1960s. It was planned that measurements would go beyond mere streamflow to include parameters of water chemistry, water quality, and stream biology. To some extent these additional parameters are being measured (Lawrence 1987).

There was established a third medium for the collection and preservation of data on geomorphic change with time, the Vigil Network. The purpose of this program is to encourage various forms of observed data recording conditions at time of survey, to be repeated at unspecified times in the future. The types of observations encouraged include monumented cross sections of channels or hill slopes, topographic or biologic transects, field maps of vegetation, and profiles of hillslopes, channels, and rills.

A major aspect of the program is that the data were stored in two places, the Laboratory of Geomorphology at the University of Uppsala, Sweden, and the library of the U.S. Geological Survey in Washington, D.C. After thirty years of operation the repositories have been moved to the Department of Physical Geography, Hebrew University of Jerusalem, and the Denver, Colorado, library of the U.S. Geological Survey. Also, the records have been put on microfiche so they are not as vulnerable as they would be in the original form alone.

The existence of the repositories has been recapitulated (Osterkamp, Emmett, and Leopold 1993), including a summary of the items presently in the collection. New entries are welcome, and information may be obtained from the authors of the summary, U.S. Geological Survey, Denver, Colorado.

The Resurveys of Watts Branch

The small stream located near Rockville, Maryland, draining 3.7 square miles, was primarily cultivated farmland in 1952, with small areas of second-growth timber. The Piedmont soil is developed on deeply weathered schist. It is red to yellow in color and erodible. In a grazed meadow through which the stream meandered, a series of cross sections was surveyed, the end points of which were monumented. In 1956 a gaging station was installed somewhat upstream of the monumented sections. The general layout of the cross sections is shown in figure 1, and the aspect of the conditions at the start of the study is shown in figure 2A.

Various studies were carried out in this research area. Direct observation was made of the process of floodplain formation (Wolman and Leopold 1957; Leopold, Wolman, and Miller 1964). The nature of bank erosion and importance of ice crystal formation (Wolman 1959), sampling of bed material (Wolman 1954), and rates of channel migration and cross-sectional change (Leopold 1973) were all surveyed on this small tract. A progress report on the hydrology and changes due to urbanization is included in Leopold (1973).

But the importance of the observational program was greatly enhanced by the junior authors, who undertook a resurvey of the cross sections in 1993–94. By this recent effort, the length of the observation program was extended to forty-one years, a relatively long period of repetitive measurement of channel change. As will be shown, the additional years of record showed changes in channel behavior that would not have been forecast from the 1953–72 period.

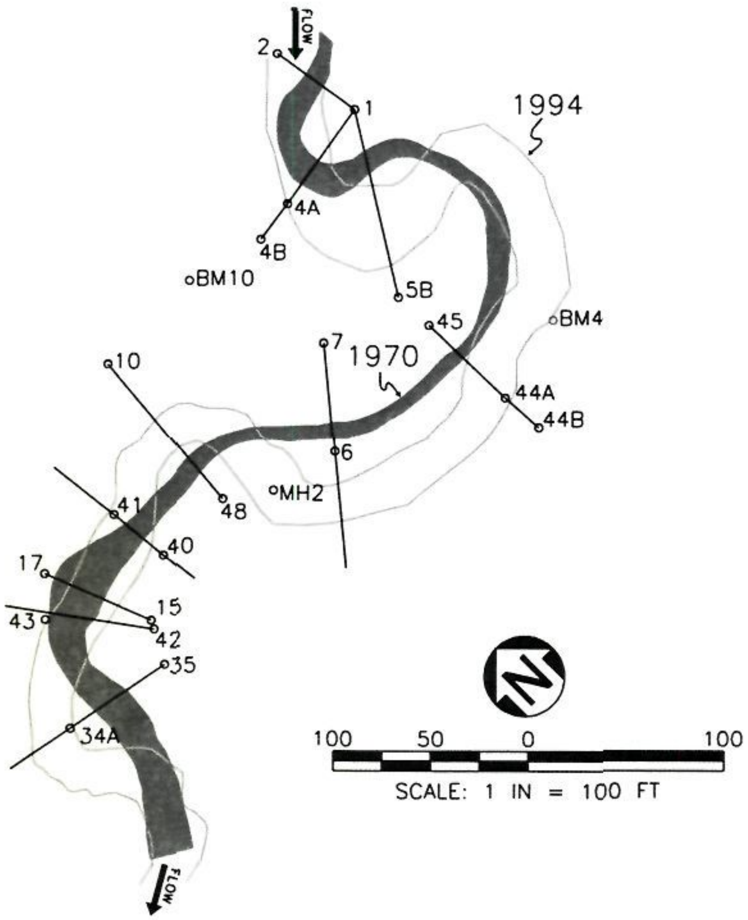


FIGURE 1. Map of study reach of Watts Branch showing channel positions in 1972 and 1994, with locations of iron pins marking the end points of cross sections

Urbanization has occurred over a large area near Washington, D.C. This process is reflected in the growth of housing and infrastructure in the basin of Watts Branch. In the 3.7 square mile basin drainage area, the number of houses or their equivalent was counted, or was computed from successive editions of the topographic quadrangle map. The increase is dramatic, as the data show:

Year	*Number of Houses on the Map*
1950	140
1955	420
1965	780
1984	2,060

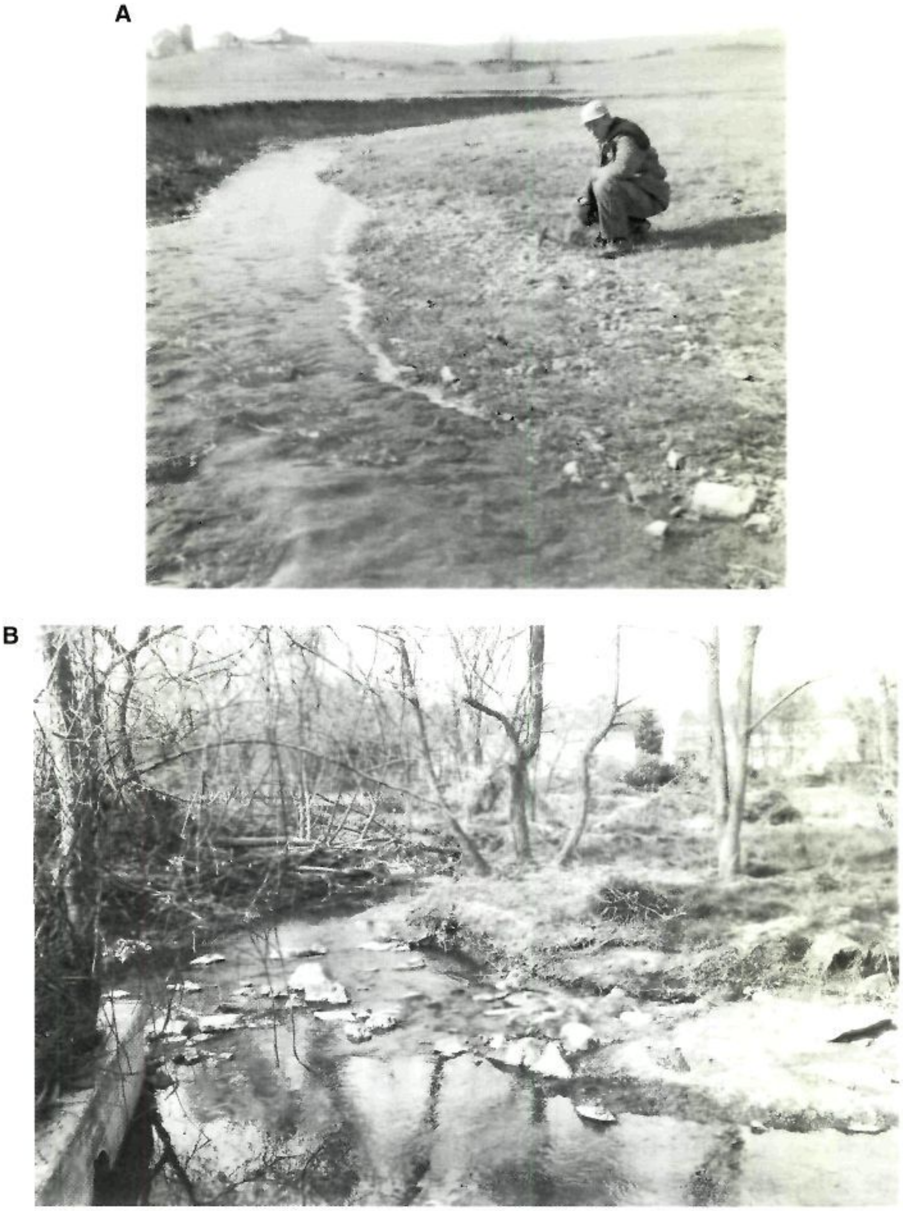


FIGURE 2. View downstream approximately at cross section 53–54. This location is about three hundred feet downstream of the map area of figure 1. Upper photo, figure 2A, taken in December 1959, shows grazed pasture and, in the distance, the original barn. In the lower photo, figure 2B, 1994, housing has replaced the farm. Large rocks in the streambed were introduced from far upstream by flood flows.

Benchmarks

An important lesson we learned is that benchmarks are fragile over long periods of time. The iron rods three feet long that were driven in the ground as the end points of a cross section are seriously eroded by the chemical action of the ground water. The brass plate benchmark on the gaging station was lost when floods carried away the concrete walls of the station. Stout spikes in trees were lost when the tree died or disappeared.

For the long term, the benchmark must be above the level of floods, and should be a concrete post enclosing a long steel pin, the surface of which is nearly flush with the ground surface. More than one benchmark should be established. None of the original benchmarks we placed in the research area survived the full forty-one years. We were fortunate in that a sewer line was constructed through the research area. It included two manholes, the covers of which provided us with better benchmarks than we had installed.

The Observational Net

Changes in streamflow may be analyzed from the records of the many gaging stations. Geomorphic effects are not measured in any comparable network. Also, there is no simple device for recording such changes. Resurvey of documented cross sections tied to recoverable benchmarks is the only practical method of observing progressive change. Perhaps the developing GPS technology might provide a simple and reproducible method of resurvey, but presently few locations, for example, those in the Vigil Network, are being measured.

The original effort in 1953 was the establishment of fifteen cross sections along a length of valley of about fifteen hundred feet. In the next few years it was clear that the results of the resurvey were interesting, so eleven additional sections were monumented and surveyed between 1955 and 1962. As the study reach became brush-covered after grazing ceased, and as overbank deposition covered large areas, finding the iron pins became increasingly difficult. A major effort at resurvey was made in 1972 despite great physical difficulty in digging down through the overbank deposits to the pins. That year fourteen sections were surveyed. In 1993–94 it was obvious that finding deeply buried pins would be possible only by use of a metal detector. This proved successful, and nine sections were surveyed.

We have learned that the resurvey of cross sections will, over any long period of time, be plagued by losses due to many causes: deterioration of monuments, erosion or decomposition of iron pins, washout as lateral movement of the channel exposes and destroys pins, inability to relocate pins, and destruction of benchmarks. Apart from permanent losses, the other major interruption of a complete record occurred when, at each resurvey, time constraints or other mundane difficulties prevented us from finding all the pins, so that not all the sections were measured.

When observations began, the locale was a grazed pasture of a working farm. Because the long-term requirements were not recognized, the ends of the cross sections were initially marked by wooden stakes. Within a few months, the mowing machine had clipped off the stakes and the whole procedure was begun anew. Thus in 1953 the three-foot-long iron pins, driven slightly below the ground surface, were installed.

After observing the increase in flood flows, we conjectured that overbank deposition, even some distance from the channel, might occur. In April of 1960 three iron pins were driven into the floodplain surface to record its elevation. These were at distances of 40, 128, and 155 feet from the channel. This seemed at the time rather a long shot because massive deposition appeared unlikely. As it turned out, even that small effort paid dividends, because floodplain deposition could not have been judged merely from channel cross sections. Figure 3 shows the profile across the floodplain. Deposition over the whole valley flat was 1.0 to 1.3 feet in depth.

In 1961 a sanitary sewer line was put in a trench that extended downvalley through the study area. Though several meander bends were destroyed and some cross sections lost, the long-term effect was beneficial. The open trench provided an opportunity to study the stratigraphy of the valley fill, and the manhole covers gave us two permanent benchmarks.

In 1962 house construction had begun on the hillslope overlooking the study area, so additional sections were established with a view to recording the effects of urbanization. Grazing of the valley floor ceased about that time.

By 1965 an interstate multilane highway had been constructed across the drainage basin just upstream of the study area, and housing had covered major portions of the basin. Brush was taking over the formerly grazed pasture. Overbank flows carrying seeds were planting them in new deposits on the floodplain surface. Thus, brush, weeds, and coarse grass, well irrigated by overflow, quickly created a jungle.

Surveys were made in 1953, 1958, 1959, 1960, 1962, 1964, 1970, 1972, and 1994. The gradual change in list of cross sections has eroded the record, yet what remains is useful. The criterion of success

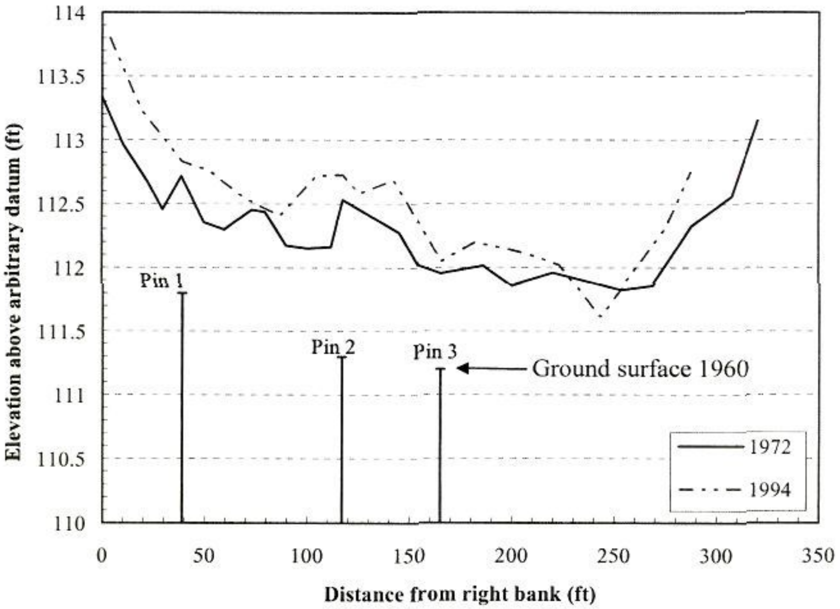


FIGURE 3. Profile of ground surface orthogonal to the channel that records overbank deposition. The three pins were driven down to the ground surface in 1960 on what appeared to the eye as a nearly level flood plain. In 1994, there had been an average deposition of more than a foot in thirty-four years.

is whether the imperfect record teaches us something about the nature and rates of landscape processes.

CHANGES IN STREAMFLOW

These developments had a marked effect on the flow regimen of the creek. The number of momentary peak discharges has increased with urbanization. It is usual for the annual flood to equal or exceed bankfull stage two years out of three. (This is the meaning of a recurrence interval of 1.5 years.) In terms of number of cases per year as judged by the partial-duration series, in a natural basin uninfluenced by humans, bankfull would be equaled or exceeded somewhat more often than once a year (recurrence interval 0.9 year).

In contrast to this normal figure, the first ten years of observation of the gaging station on Watts Branch recorded twenty cases of discharge above bankfull, or two per year. In later years the number of overbank flows increased from two to seven in three decades of observation. The number of times various discharge values occurred is tabulated below.

Time Period	*Number of times discharge exceeded these thresholds*	
	220 cfs	*350 cfs*
1958–67	20	10
1968–77	74	32
1978–87	73	32

Another indication of the effect of urbanization is the value of the mean annual flood, recurrence interval 2.3 years. The mean annual flood is the average of the highest peak discharge each year.

Annual Flood Period	*Average Flow*
1958–73	781 cfs
1973–87	959 cfs

MATERIAL ON THE STREAMBED

The increase in magnitude of the floods changed the bed material in the channel, as seen in figure 2. The many large angular rocks present in 1994 could not have come from bank erosion in the valley fill, because the alluvium is silt-clay and the original bed had inconspicuous riffles made up of fine gravel having a D50 of about 16 mm. Rounded gravel a few feet under the streambed was observed in the sewer trench, but because the bed was aggrading this could not be the source. We believe that the angular blocks of large size were carried into the reach by floods, excavated from the many sites upstream cleared during construction.

CHANNEL CHANGES

There are presented in figures 4 to 7 plots of cross sections that typify the changes occurring in the years of record. The figures present cross sections in the downstream sequence.

Figure 4 includes two of the cross sections originally established in 1953. These plots show no appreciable bed aggradation at or until after 1960, but great widening in the same period.

Figure 5A shows considerable widening after 1961. Immediately downstream at section 6–7, a great burst of lateral motion and consequent deposition moved the channel laterally and built the bed about two feet vertically. The lateral movement through this reach washed out the iron pin at Station 44; it was replaced at a position farther from the bank.

Figure 6A shows the channel building its bed by deposition after 1970 as well as channel enlargement. At Section 40–41 in figure 6B,

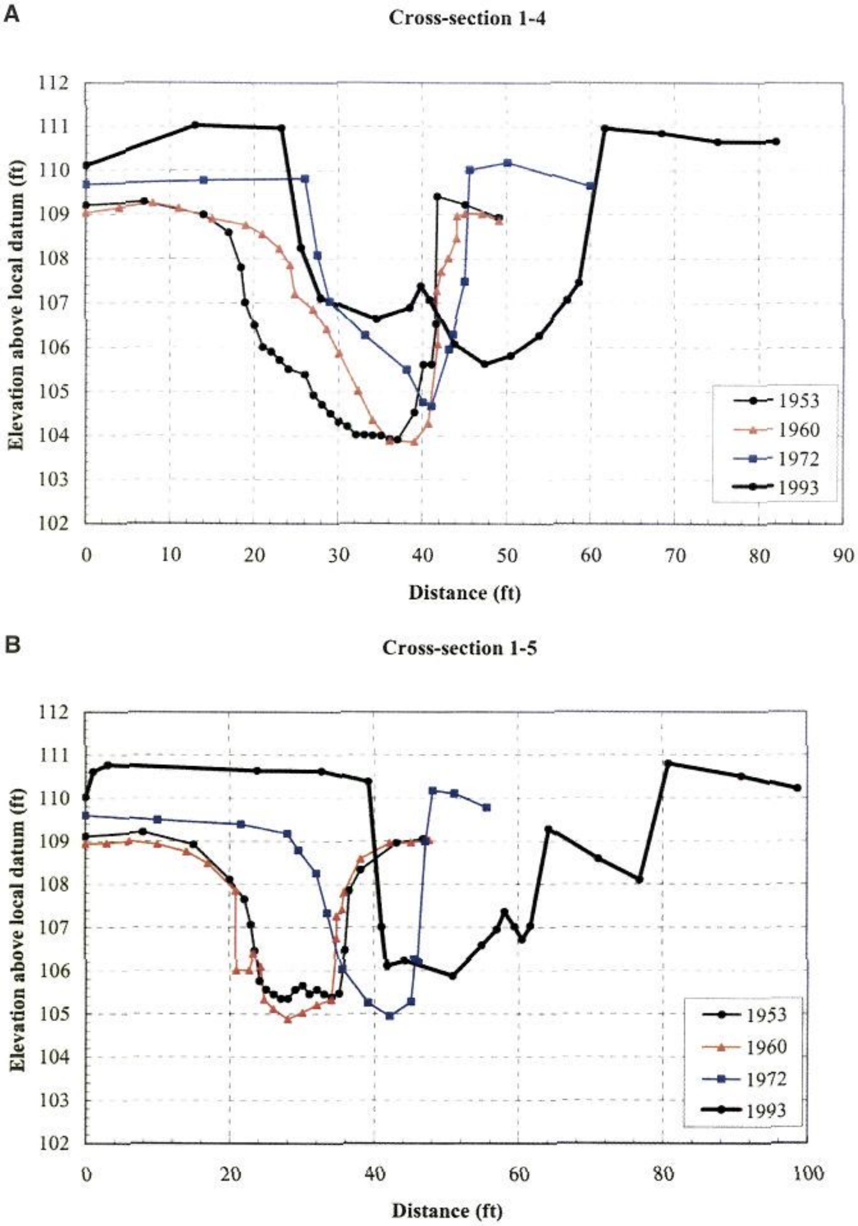
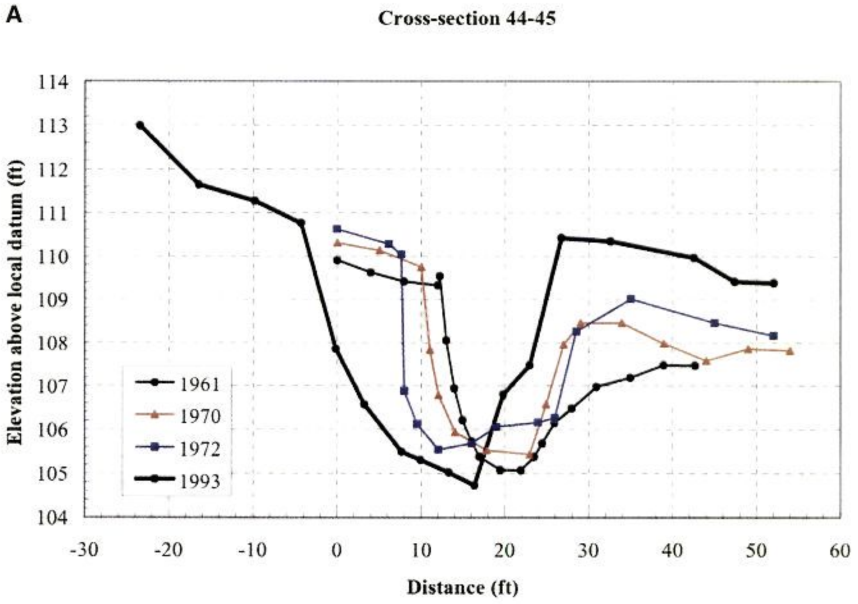


FIGURE 4. Cross sections first surveyed at the beginning of the observational period, 1953, and also in 1993. The aggradation on the streambed and flood plain was accompanied by an increase in width.



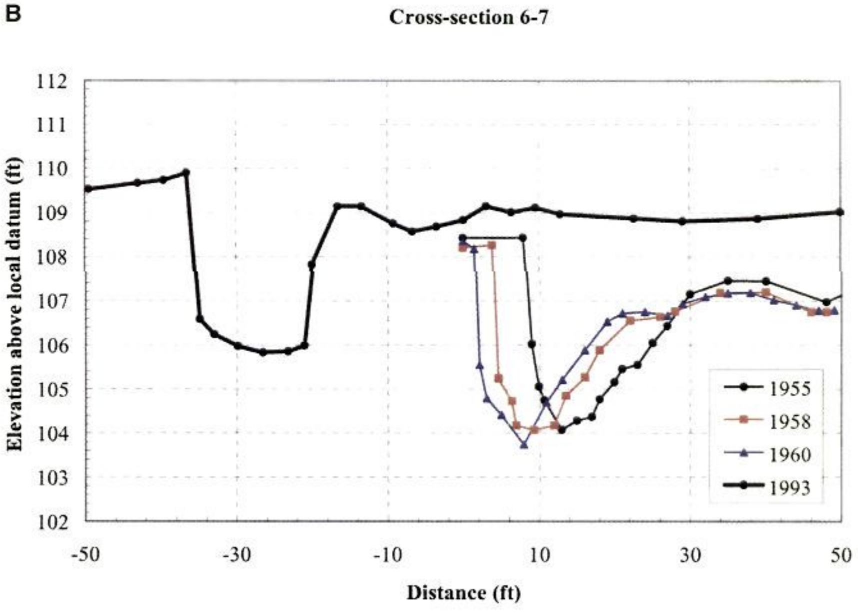


FIGURE 5. Section 44–45 had experienced a large increase in width and overbank deposition, but without bed aggradation. Section 6–7 moved laterally a large distance and aggraded its bed.

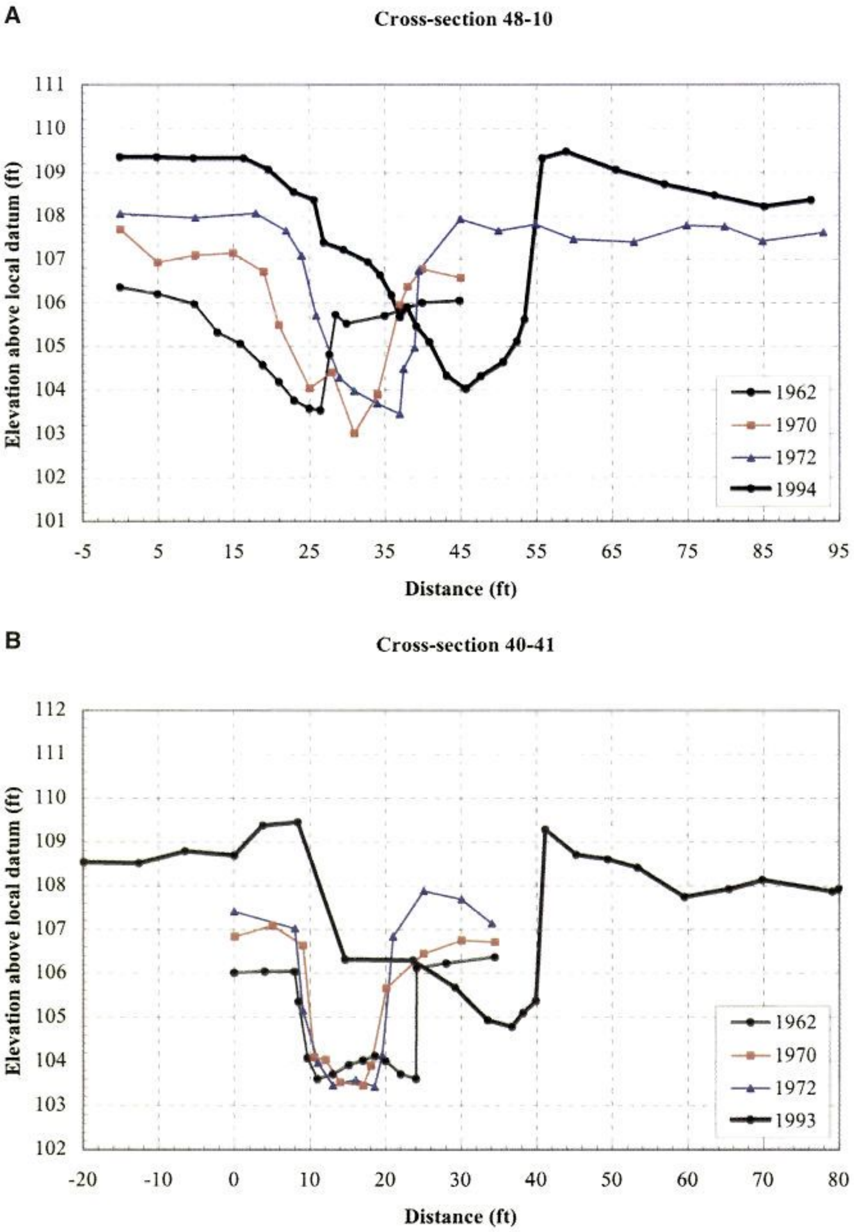
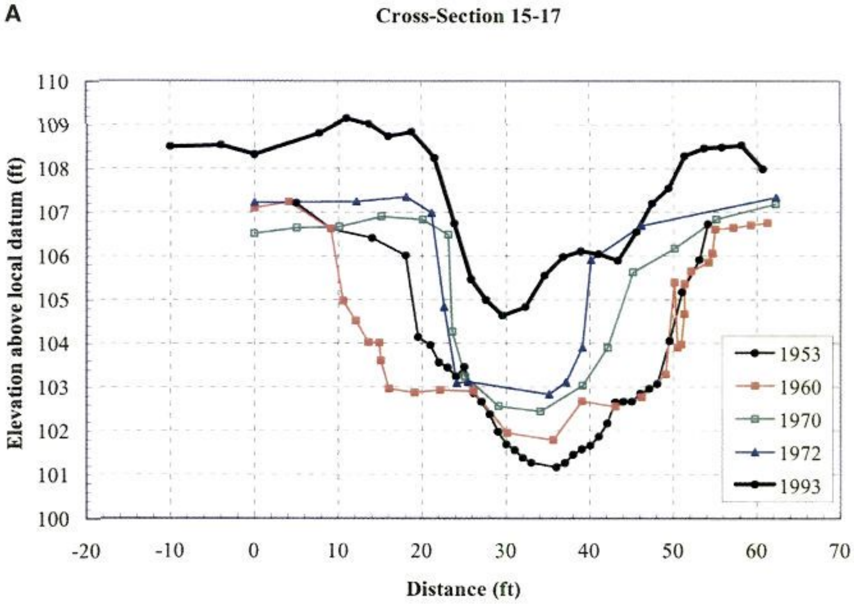


FIGURE 6. Section 48–10 had impressive point bar development with 5 to 6 feet of deposition in thirty-two years. Section 40–41 did not change width in the first ten years, but greatly increased width in the next twenty years.



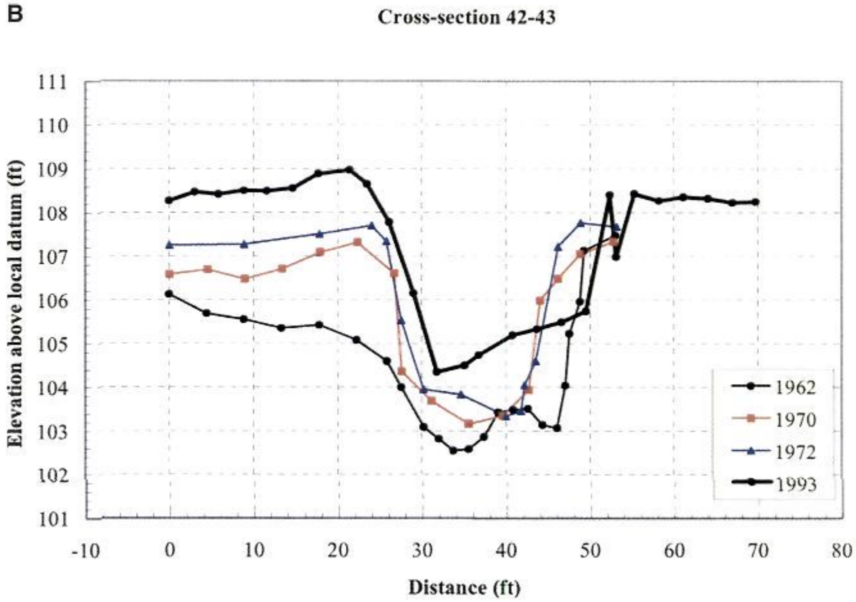


FIGURE 7. Section 15–17 aggraded its bed, but with only modest decrease in channel area. Section 42–43 showed massive deposition on the point bar of the left bank.

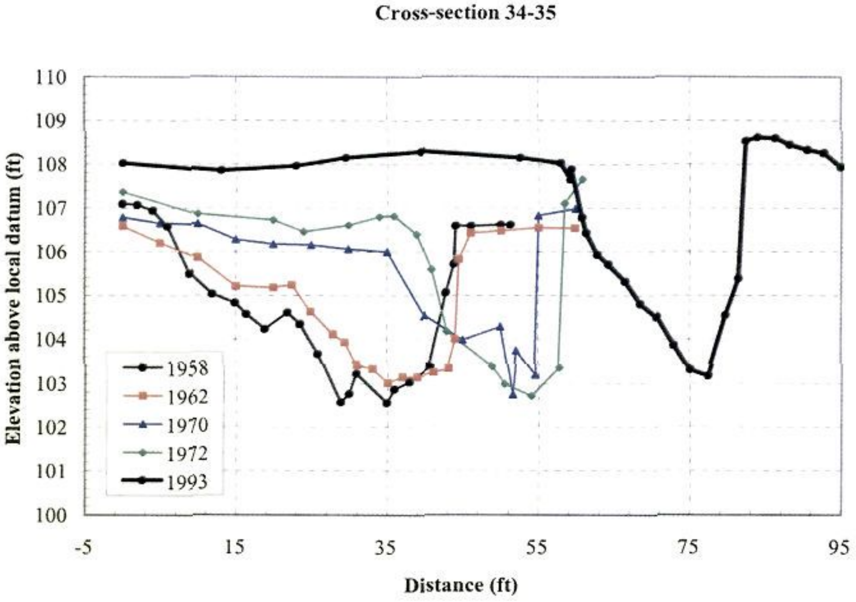


FIGURE 8. Section 34–35 moved progressively, but the largest deposition on the point bar was after 1972.

the channel had remained nearly the same size with merely some overbank deposition between 1962 and 1972, but from that year to 1993, the bed increased elevation by nearly 3 feet, and the channel doubled its area. Figures 7A and 7B show bed aggradation after 1970 as well as overbank deposition without much change in area, but massive change after 1972. In figure 8, the channel at Section 34–35 moved progressively from 1958 to 1993, with greatest deposition in the last twenty years of the period.

Where narrowing occurred, it was due to massive point bar development. To specify changes in channel width is complicated because of simultaneous change of channel shape. The change in shape and increase in width/depth ratio is obvious between 1972 and 1993. Nearly all of the sections demonstrate this.

Although even adjacent cross sections did not experience the same changes, there is a general sequence that can be seen. Thalweg elevations increased due to bed aggradation. Comparing the bed elevations at date of installation to 1972, ten sections showed an increase from 0.5 to 1.2 feet, and three sections showed decrease of −0.1 to −0.2 feet. Comparing original bed elevations with 1993 conditions, eight sections showed an increase of 0.3 to 3.6 feet, and one a decrease of −0.1 feet.

Rounding the scattered data, the deposition rate on the streambed averaged about 1 foot in forty-one years, or 0.02 ft/year. This is just about equal to the observed rate of aggradation on the valley floor. This unique observation is especially interesting. In many valleys, especially in semiarid regions, aggradation had caused the deposition of thousands of acre feet of sediment, often silt or silt-clay. In some valleys of the American Southwest, the valley fill is 80 to 100 feet in depth. The nature of the channels associated with these deep deposits has been a matter of speculation. It is easy to imagine deposition by braided channels, wandering back and forth across the valley floor, the streams being wide and shallow, and having no definite cross-sectional form. But direct observation on rapidly aggrading valleys in Nebraska showed that the channels maintained definite form with usual width/depth ratio, while bed aggradation was approximately equal to overbank deposition (Leopold 1978). The Watts Branch data confirm the Nebraska observation that valley aggradation can take place while channels maintain their geometry, because overbank deposition is nearly equal to the rate of bed aggradation.

The 1972 analysis of channel change reflected twenty-nine years of observation. In the first two decades, the channel slowly contracted in area by some plastering of new sediment on the channel banks and massive point bar deposition. This was accompanied by deposition overbank, especially in the near-channel zone. Of seventeen cross sections, eleven experienced a decrease in area. These had an average area of 73 percent of the original value. The six sections that increased in area averaged 1.6 times the original area.

But in the succeeding two decades, 1973 to 1993, channel width increased greatly and overbank deposition appeared to add only minor amounts of sediment on the valley floor. The channel changes were coincident in time with the expansion of urban development. In the period 1950–55 the number of houses added per year in the drainage basin was fifty-six. In the period 1965–84 there were sixty-seven houses added per year But ten years later, in 1994, we drove through well-kept neighborhoods in the basin, an apparently affluent portion of the expanding city of Rockville. There were no open lots and no buildings under construction. It seemed clear that there was no more room for additional buildings. In this area where the annual precipitation is near 44 inches, trees grow rapidly and any open space tends to be quickly claimed by shrubs and trees. The valley flat, formerly a grazed pasture, is now a local county park, portions of which are grassed rather than forested. This is because the county mows some portions of the park to promote public access.

In 1994 the cross sections show a channel much wider than in 1972. It is also lined with brush, except in areas too shaded by trees to

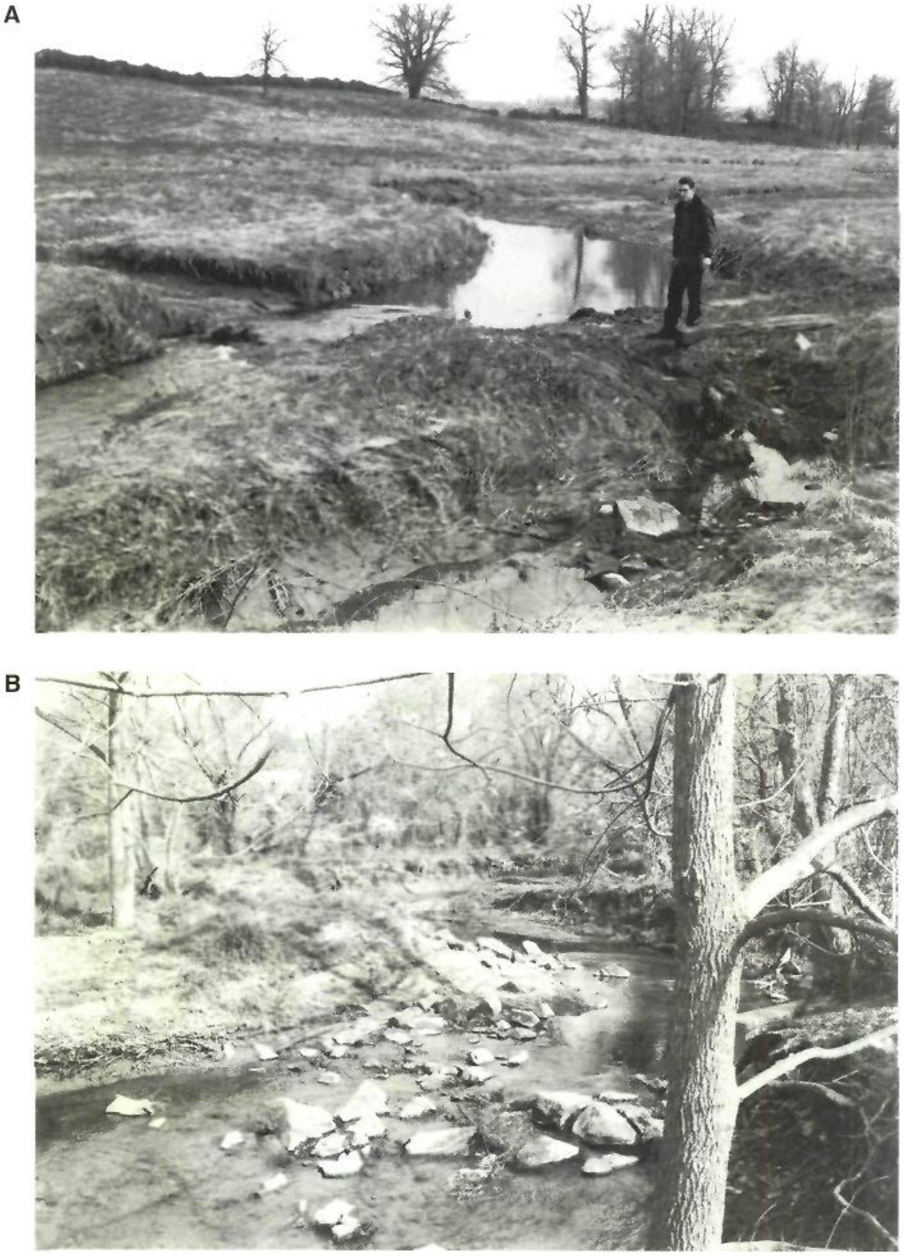


FIGURE 9A. View upstream in 1962 near a small island at Section 42. In 1994, figure 9B shows large angular rocks that had been brought in by floods.

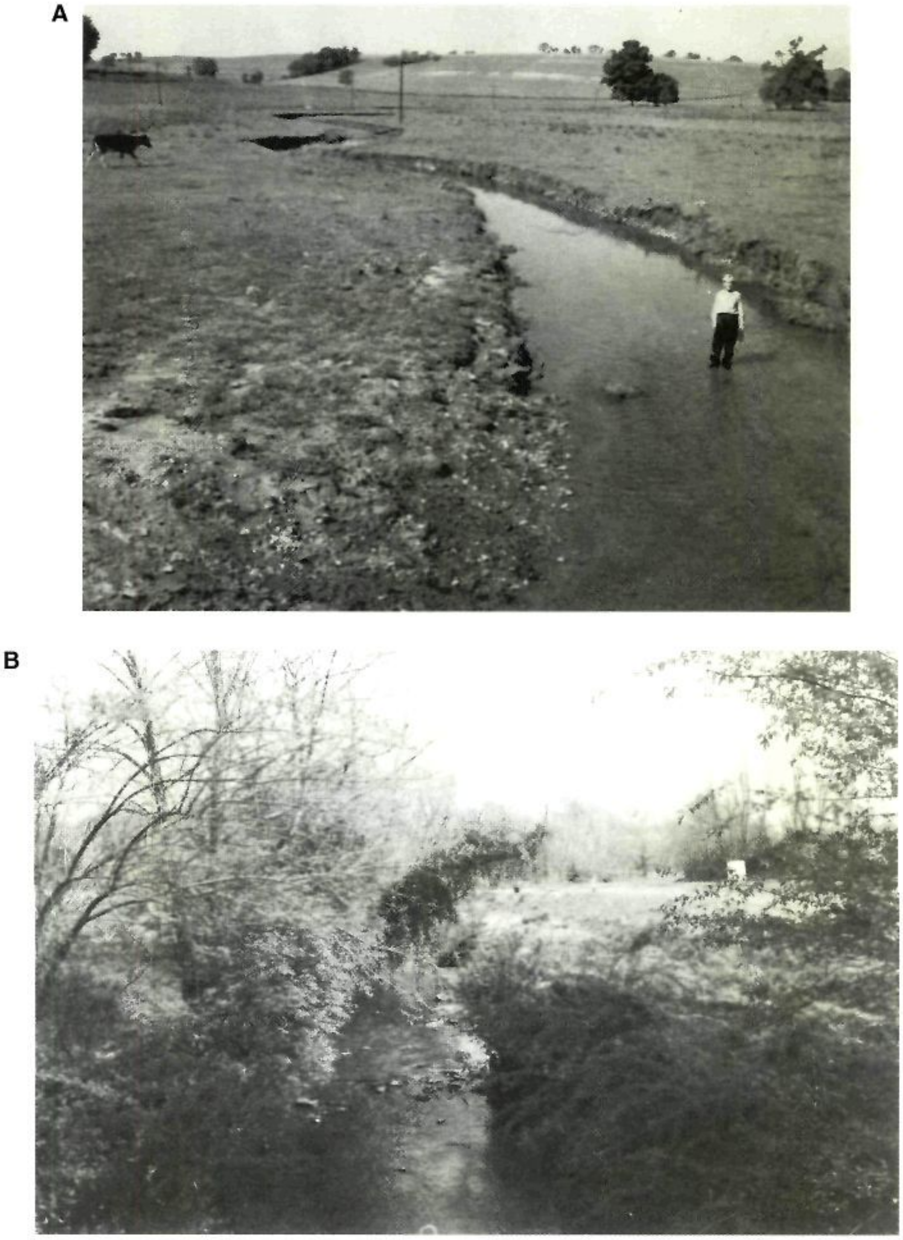


FIGURE 10A. View upstream in 1954 from bridge at lower end of the study area. Figure 10B shows the same view in 1994.

FIGURE 11A. View downstream in 1961 showing manhole far to the left of the channel. By 1994, in figure 11B, the channel had moved so far that the manhole stood in the center of the stream.

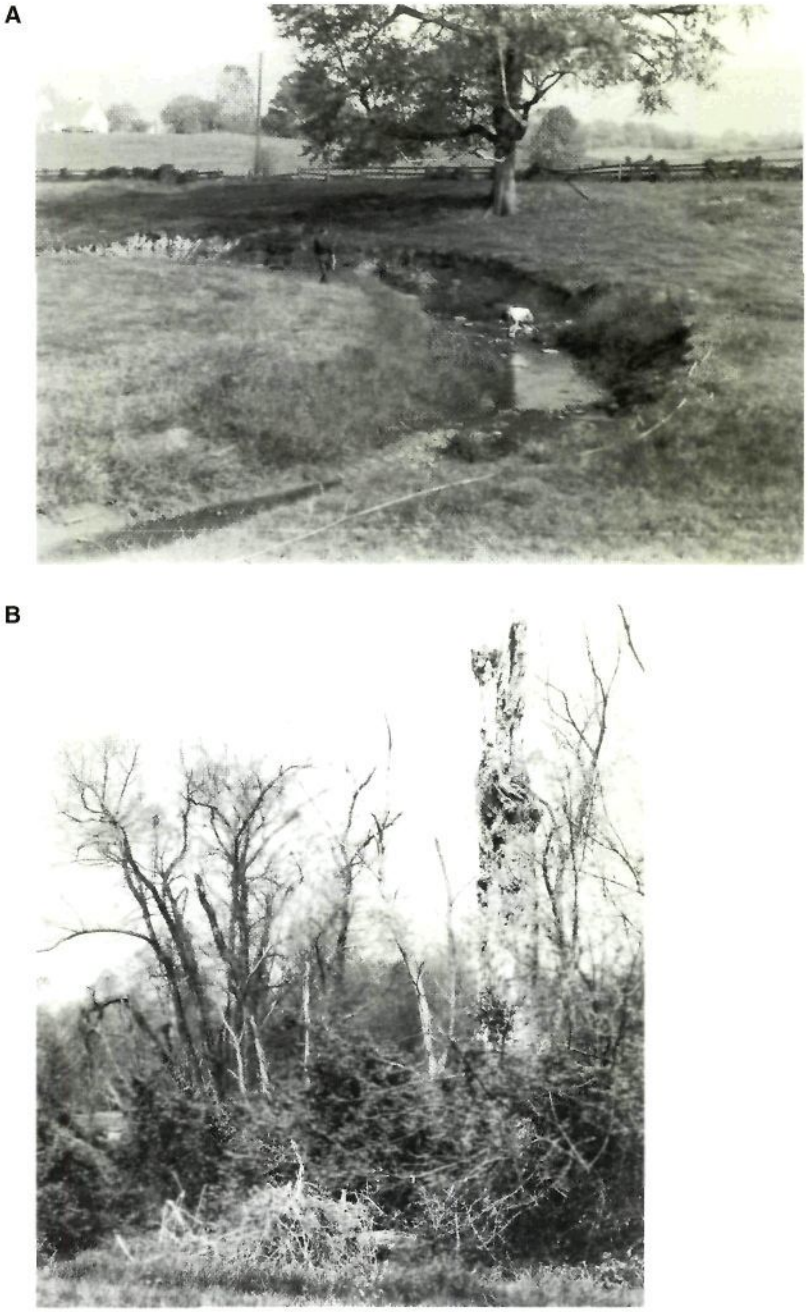


FIGURE 12A. View upstream in 1954 toward the maple tree on the roots of which we had put one of the principal benchmarks, BM 4. In figure 12B, photographed in 1994, the maple tree, now dead, has its roots eroded away by lateral movement of the stream. The channel is hidden in the brush at the bottom of the photo.

have a conspicuous understory, or is mowed as a public amenity. On a spring weekend in 1994 there were several fishermen using the research reach, and other citizens strolled through the open areas.

These observations lead us to suggest that there is an urbanization cycle in small river basins. A late portion of this cycle could not have been foreseen with the first twenty years of observation, and perhaps the available forty-one years is still too short a period to visualize its completion. The terms or time periods mentioned are only approximate, and probably vary among cities and among regions.

Stage 1. Duration ten years. Housing, roads, and sewers are constructed. The urban stream is resilient, and though flood discharges increase, channel changes are minimal.

Stage 2. Duration ten years. Development of roads and buildings continues, and many sites are cleared for construction. These are particularly subject to erosion during the rainy and snowmelt seasons. The stream channels react to the increased frequency of high flows and sediment production by depositing sediment overbank, by plastering sediment on the channel margins, and by massive point bar development. Channels become narrower as a result. Shading of the water is minimal, and water temperatures are high in summer. Fish are decimated.

Stage 3. Duration twenty years. Development proceeds. Some reaches of stream are buried in pipes or straightened and put in concrete. Toward the end of the period there is a shortage of building sites. The older neighborhoods are well vegetated and are hydrologically stabilized, but the stable state reflects the large areas of roof and pavement. The number of high discharges per year has increased and overbank flows are common, but sediment production decreases as the number of construction sites becomes scarce. Channels widen because of common high discharges and concurrent decrease in sediment load. The temperature of water in channels is high.

Stage 4. Duration ten years. New building nearly ceases because there are no more sites available. The neighborhoods mature, and lawns, trees, and gardens provide nearly complete cover. Sediment production is low because roads, roofs, and other impervious areas do not have erodible area, but high flows are frequent. Channels are wide and migrate by erosion where banks are not stabilized by trees or revetments. Where streams are not in pipes or concrete, open reaches become parks.

Stage 5. Duration unknown. New construction is nearly absent. Some parts of the public wish stream channels to be revitalized and made more natural. Some reaches are exhumed at great expense. Water temperatures are cooler because of shading by trees. Some fish return.

Watts Branch has been through the first four stages, and the last stage can be foreseen. Perhaps by recognizing the sequence of steps in the progress of urbanization, some of the deleterious parts of the sequence can be shortened or eliminated.

The sequence of events in urbanization as described above is common. The contribution made by the Watts Branch example is the establishment of a quantitative base in real time and with actual measurements, but the succession of events can be seen in many communities. Our analysis is an elaboration of the sequence of events observed in small basins in England, including one near Exeter, Devon, described by K. J. Gregory (1978).

The generality of our observed sequence exposes in stark terms the ethical and aesthetic responsibility to balance community amenities against the powerful forces for development, for expansion, and for short-term profit. It is well known that urban expansion is usually advertised as an overall benefit in jobs, increased value, and contribution to net worth. But unarticulated and often purposely hidden are the losses in amenity value, in undisclosed costs—economic, environmental, and aesthetic. One of the perversions pressed upon an unsuspecting public is the benefit-cost ratio that consistently fails to include costs to society that may be delayed. These delayed costs are often of a nonmonetary nature, and fall to a group other than the one that reaps the benefits. The costs include deprivation of the aesthetic and educational value of a free-flowing stream in the community. Many towns have paid the long-delayed cost in excavating part of a channel length from its concrete strait jacket. The erosion commonly experienced at the lower end of a concreted or piped reach of channel is a direct monetary cost seen in remedial engineering.

But perhaps the most discouraging cost is the avoidance of ethical responsibility for the health of an ecosystem. Though the general public has not yet appreciated it, the communal value of biodiversity is increasingly recognized for its monetary as well as its other values, though the acceptance of the inherent rights of nature is slower and more distant. At present only a small portion of the affluent American society is willing to see its ethical responsibility, even to its own immediate natural landscape. Its commitment to ecosystem preservation in distant lands, inhabited by strange people, is even less urgent. But as pressures on water, mineral, soil, and biologic resources increase throughout the world, the need for an operational land ethic will sooner or later be made real and personal to the public in advanced nations. To begin that process, we might best make it flower in our own backyard.

ACKNOWLEDGMENTS

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