Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter C1

FLUVIAL SEDIMENT CONCEPTS

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Book 3

APPLICATIONS OF HYDRAULICS

Denudation

The net result of sediment erosion, transport, and deposition is a leveling of the continents, because all transport is toward a lower level. Though denudation rates are highly variable over a given area, they are generally expressed as a uniform lowering of the land surface in feet or inches per 1000 years, or years per foot. Usually, the dissolved-solids load of a stream accounts for a considerable part of denudation. The dissolved-solids and sediment yield of stream basins is usually measured in terms of tons per square mile per year. Therefore, using a minor rearrangement of an equation presented by Dole and Stabler (1909),

$$D=0.0052\ Q_s,$$

where D is denudation in inches per 1000 years and Q_s is sediment yield in tons per square mile per year.

Rates of denudation, based on both dissolved-solid and sediment loads for seven regional areas, are given in table 5 as previously published by Judson and Ritter (1964). These areas include all the United States except the drainage of the Great Basin, the St. Lawrence River, and the Hudson Bay areas. Holeman (1968) has used this information together with other fluvial-sediment data around the world to show that about 20 billion tons of sediment is transported to the oceans each year. This represents 2.7 inches per 1000 years of denudation and an average yield of 520 tons per sq mi. The Holeman estimate is close to Schumm's (1963) estimate of 575 tons per sq mi and 3 inches per 1000 years.

Geomorphic aspects

Rains occur even in the most absolute deserts, though infrequently. Thornbury (1954) suggests that even desert landforms are mostly the work of running water. Some understanding of the geomorphic aspects of drainage areas will assist in the work of obtaining useful fluvial sediment data. Likewise, as indicated later, good fluvial sediment data will be useful to the geomorphologist.

The drainage basin

The drainage basin forms the natural unit for geomorphic consideration with respect to fluvial sediment. Drainage of excess rainfall from the basin occurs as overland or sheet flow by gravity across the planelike upland areas; with sufficient accumulation of depth and velocity, erosion occurs to form a network of drainage channels. The detail and extent of the recorded drainage system frequently depends on the detail of the map used. The network may be described in various venation terms such as trellis or palmate.

Small rills are integrated into a drainage net on a fresh surface by cross grading and micropiracy (Leopold and others, 1964, p. 411). Cross grading occurs during very heavy storms when water overtops the rill divides and erodes paths that reduce the flow in the upper rill and increase the flow to an adjacent lower rill. Micropiracy may occur with smaller storms when a small channel's drainage system is robbed by a larger channel. Further development of the drainage net will take place as each new com-

Table 5.—Regional denudation in the United States

Drainage region	Drainage area (1,000 sq mi)	Average load (tons per sq mi per year): Dissolved solids	Average load (tons per sq mi per year): Sediment	Total denudation (inches per 1,000 years)
Colorado River	246	65	1, 190	6. 5
Pacific slopes	117	103	597	3. 6
Western Gulf of Mexico	320	118	288	2. 1
Mississippi River	1, 250	110	268	2. 0
South Atlantic and eastern Gulf of Mexico	284	175	139	1. 6
North Atlantic	148	163	198	1. 9
Columbia	262	163	125	1. 5

ponent of the eroded slope allows a slightly different system of cross grading and as larger channels pirate or rob smaller ones.

In consideration of a whole drainage basin, Horton (1945) was among the first to recognize the relationship of stream length and stream number to stream order. Stream order is a measure of stream position in the net with respect to its upstream collection. A first-order stream has no tributaries, a second-order stream has only first-order tributaries, a third-order stream has only first- and second-order tributaries, and so forth. Also, the longest tributary from the stream segment of the largest order is extended headward to the drainage area of all streams draining to a site on the stream of the given order. Horton also introduced the term "bifurcation ratio" to express the ratio of the number of streams in a basin of any given order to the number of the next lower order. This ratio tends to equal about 3.5 for many basins in the United States, especially when considering only stream nets shown on maps at a scale of 1:24,000.

In a study of hydrographs from small basins in Pennsylvania, McSparran (1968) defined several drainage-basin characteristics as follows:

1. Area, A, as the square miles of area enclosed by the water divide.
2. Length, L_s, as the distance in miles along the stream to the most remote point on the divide.
3. Slope, S, as the geometric average slope of the profile taken along the stream used to determine L_s.
4. Drainage density, D_d, as the ratio of the total length of all streams in the basin (from USGS 1:24,000-scale maps) to the drainage area.
5. Basin shape factor, F, as the ratio of the length to the remote point, L_s, to the diameter of a circle with an area equal to the drainage area.

Generally basin length, L, is simply defined as the maximum distance from the basin mouth to the water divide, and basin shape factor and slope are defined using L instead of L_s. Schumm (1954) successfully related mean annual sediment loss for a variety of small drainage basins in the Colorado Plateaus province to a basin-relief ratio defined as the ratio between total basin relief and basin length, L. Position along the curve indicates the relative resistance of a given basin to sediment erosion.

Mass wasting

Mass wasting, or the gravitative transfer of material toward and into the streams, has some degree of importance. Too often only the precipitous or very notable types are recognized. Sharpe's classification (1938) of mass-wasting types has come into general usage, and it is sufficient to quote his classes and their definitions directly from Thornbury (1954, p. 45–46).

Slow-flowage types:
- **Creep:** The slow movement downslope of soil and rock debris which is usually not perceptible except through extended observation.
  - **Soil creep:** Downslope movement of soil.
  - **Talus creep:** Downslope movement of talus or scree.
  - **Rock creep:** Downslope movement of individual rock blocks.
  - **Rock-glacier creep:** Downslope movement of tongues of rock waste.
- **Solifluction:** The slow downslope flowing of masses of rock debris which are saturated with water and not confined to definite channels.

Rapid-flowage types:
- **Earthflow:** The movement of water-saturated clayey or silty earth material down the low-angle terraces or hillsides.
- **Mudflow:** Slow to very rapid movement of water-saturated rock debris down definite channels.
- **Debris avalanche:** A flowing slide of rock debris in narrow tracks down steep slopes.

Landslides: Those types of movements that are perceptible and involve relatively dry masses of earth debris.
- **Slump:** The downward slipping of one or several units of rock debris, usually with a backward rotation with respect to the slope over which movement takes place.
- **Debris slide:** The rapid rolling or sliding of unconsolidated earth debris without backward rotation of the mass.
- **Debris fall:** The nearly free fall of earth debris from a vertical or overhanging face.
- **Rockslide:** The sliding or falling of individual rock masses down bedding, joint, or fault surfaces.

Rockfall: The free falling of rock blocks over any steep slope.

Subsidence: Downward displacement of surficial earth material without a free surface and horizontal displacement.

Thornbury further states,

The conditions which favor rapid mass wasting were divided by Sharpe (1938) into passive and activating or initiating causes. **Passive causes** include: (1) **lithologic factors,** unconsolidated or weak materials or those which become slippery and act as lubricants when wet, (2) **stratigraphic factors,** laminated or thinly bedded rock and alternating weak and strong or permeable and impermeable beds, (3) **structural factors,** closely spaced joints, faults, crush zones, shear and foliation planes, and steeply dipping beds, (4) **topographic factors,** steep slopes or vertical cliffs, (5) **climatic factors,** large diurnal and annual range of temperature with high frequency or freeze and thaw, abundant precipitation, and torrential rains, and (6) **organic factors,** scarcity of vegetation. **Activating causes** are: removal of support through natural or artificial means, oversteepening of slopes by running water, and overloading through water saturation or by artificial fills.

The reader can recognize from these descriptions that streams can be altered with respect to width, slope, and sediment load by one or more of the many forms of mass wasting. The mudflow, for example, has been treated by Croft (1967) as a problem in public welfare because of its notable occurrence in the form of a "catastrophic event." These can occur on steep-sloped streams draining areas where vegetation and soil have been damaged on a significant part of the drainage basin. Such debris floods are often of short duration, frequently an hour or less, and carry very heavy concentrations of sediment, sometimes with boulders ranging up to several tons in size. Croft (p. 9) reports an hypothesis for the movement of boulders as follows:

While the debris flow is confined to narrow canyon walls, the boulders are almost completely submerged in the semifluid concretelike matrix with a density of about two. The push exerted downslope by the mass and the ball-bearing effect of smaller rocks are important factors in forward motion. An example of movement by pushing and rolling is the 8-ton boulder at the forward end of the Kay Creek mud-rock flood of 1930. This boulder moved about a quarter mile from the canyon mouth across slopes averaging 8.3 percent.

Channel properties

At a given time, the drainage network is a highly organized complex system of physical and hydraulic features which route excess water and weathered products from higher to lower elevation. At a given location in a channel, the tangential stress of flow on the channel boundary is equal and opposite to the resistance exerted by the bed. The transmittal of this shearing stress or exchange of momentum from layer to layer in the flow causes a gradient in the flow velocity. With respect to the energy involved, the slope of the water surface is a direct measure of the energy exchange where there is no velocity change at a point (steady flow), and where there is no change in velocity with distance along the channel (uniform flow). The ultimate fate of the potential energy derived from movement of the flow along the slope is conversion to heat.

With the fact in mind that most of the energy dissipation in open channels is proportional to the square of the flow velocity, Leopold, Wolman, and Miller (1964, p. 162) suggest the possibility of three types of resistance. The first type is skin resistance, caused by the roughness that is in turn determined by the size and character of the material in the bed and banks. For a given roughness, the amount of resistance varies with the square of the flow velocity. The second type is internal distortion resistance, caused by boundary features such as bank protuberances, bends, bars, or individual boulders that set up eddies and secondary circulations. Resistance from these features is also proportional to the square of the mean flow velocity. The third type is spill resistance, where energy is dissipated by local waves and turbulence caused when a sudden reduction in velocity is imposed. In a natural stream these individual resistance types cannot be measured; the total dissipation, however, is indicated by the longitudinal profile of the stream.

Hack (1957) indicates that the longitudinal profile of a stream may be controlled by several factors that are related to both the physical and the chemical properties of the bedrock. Therefore, the sediments found in streams with a given bedrock and similar climate and vegetation are likely to have unique size characteristics at different points along the channel. Hence, stream slopes are expected to be similar for geologically similar areas. Figure 21 from Hack shows how the stream slope changes along its length for several areas of similar bedrock. Such definitive slope patterns would be less distinguishable in larger basins which have more complicated geology, climate, and vegetative controls.

In many streams, vegetation such as grass, weeds, willows, and trees may affect the channels' resistance to flow, especially in the part of the channel above the "normal" flow. Often a high flow will remove, partly remove, or bury the lower types of such vegetation; this removal or burial causes considerable change in resistance during the period of the runoff event.

Omitting vegetation, channel resistance to flow is largely a function of the sizes and shapes of grains or particles, the microfeatures, and the larger boundary or macrofeatures. A bed of large irregular-shaped particles will offer more resistance than a sand-gravel complex. Figure 22 gives the size distribution of bed material for several streams at gaging stations. These distributions represent sizes found for most

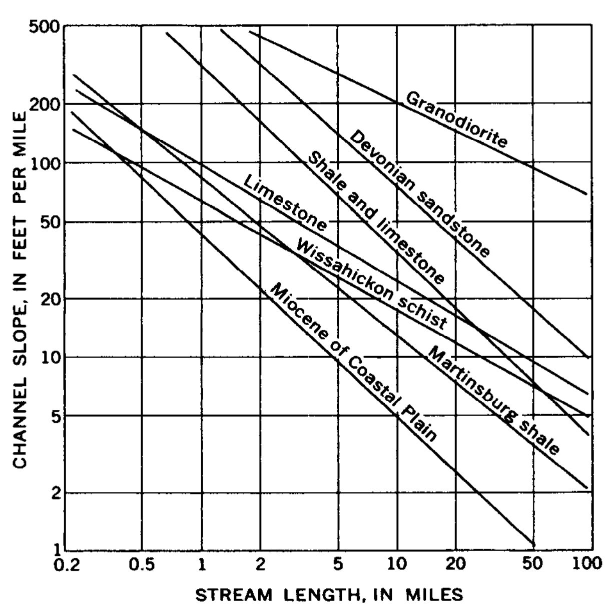


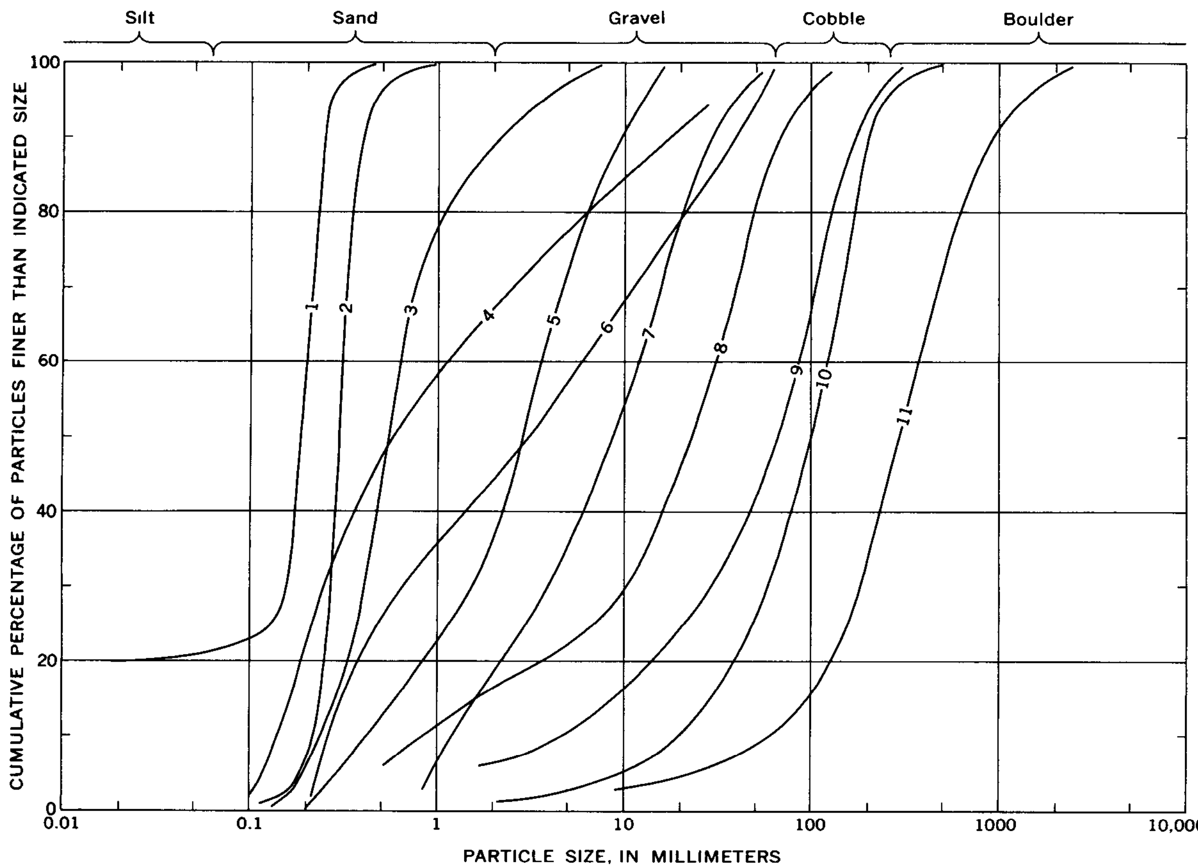
Figure 21.—Average relation between channel slope and stream length for seven geologically different areas in Maryland and Virginia. From Hack (1957, p. 88).

streams. Note that distributions to the left of a median size (50 percent) of about 1 mm would be called sand-bed streams. The resistance to flow for the different bed forms for sand-bed streams has been discussed on page 16. The distributions with respect to some of the streams plotted in figure 22 also indicate that the particle size of bed material tends to become finer in the downstream direction. Even in the 1,000-mile reach of the Mississippi River between Cairo, Ill., and New Orleans, La., the median size decreases from about 0.65 mm to about 0.20 mm.

In addition to the bed forms and other macrofeatures already described, it is well to note that sand-bed streams may form large moving bars or sand waves. Carey and Keller (1957) describe sand waves in the Mississippi River as much as 10 meters high and up to 3 km long, on which smaller waves or dunes were noted. Alternate bar formation has also been observed in laboratory flume experiments (Simons and Richardson, 1966). Erosion on the streambank opposite alternate bars may be a factor in the development of stream meanders.

In streams where gravel-sized material or larger is present on the bed, the development of pools and riffles is common, especially in the smaller streams. The spacing of riffles in both straight and meandering channels appears to suggest that the same wave phenomenon that creates the meander is also operating in the straight channel. Riffles in rivers are of lobate shape extending alternately from the banks so that the low-water flow bends around the nose of each riffle. The bends cause a sinuous course even when the stream banks are rather straight.

Alluvial streams characteristically tend to meander; that is, they develop a series of rather symmetrical alternate bends that may grow in lateral extent and at the same time migrate downstream. Among the many who have found empirical relations between such variables as meander length, meander-belt width, channel width, and radius of curvature, Jefferson (1902) was one of the first to recognize specific meander characteristics. Leopold, Wolman, and Miller (1964, p. 298) in a study of stream meanders on 50 rivers of different sizes and from



1— Mississippi River at Head of Passes, La.
2— Mississippi River at Cairo, Ill.
3— Missouri River at Omaha, Nebr.
4— Republican River at Clay Center, Kans.
5— South Platte River at South Platte, Colo.
6— Pembina River at Walhalla, N. Dak.
7— Seneca Creek near Rockville, Md.
8— Brandywine Creek at Lenape, Pa.
9— Brandywine Creek at Cornog, Pa.
10— Yellowstone River at Billings, Mont.
11— W. Fork Rock Creek near Red Lodge, Mont.

Figure 22.—Particle-size distribution of streambed material typical of indicated streams in the United States.

different physiographic provinces found that the ratio of the radius of curvature to stream width averaged 2.7 and that two-thirds of the values were in the range 1.5 to 4.3. If the meander length (wavelength) is about 10 times the stream width, then the radius of curvature is about one-fourth of the meander length.

The highest velocity of flow in several cross sections around a meander is usually near the concave bank a bit downstream from the axis of the bend. The velocity in a meander crossover is usually somewhat higher on the side of the concave bank upstream. A generalized diagram of the velocity distribution at five cross sections in half a wavelength is shown in figure 23. These velocity patterns in the meander system suggest that the maximum erosion of the concave bank should occur just downstream of the axis of the bend. Friedkin (1945) noted that sand eroded from a concave bank in a laboratory "river" was generally deposited on a point bar downstream on the same side of the channel. This would be expected because the superelevation of the flow toward the concave bank would in turn cause a sidewise current on the streambed from the outside to the inside of the bend. This is suggested to be part of the mechanism of point-bar building and maintenance. The concentration of suspended sediment should be nearly uniform across the section slightly downstream from the crossover (section 1, fig. 23) between the bends because there should be no sidewise current at this location. As the flow moves into and somewhat past the center of the bend (section 3, fig. 23), the intensity of the crosscurrent increases toward the concave bank on the stream surface and toward the convex bank on the streambed. The sidewise current along the bed carries the heavier concentrations and larger particles from the deeper part of the section toward the shallower part near the convex bank.

Experiments with models at the Waterways Experiment Station (Lipscomb, 1952) show that the size of bends (meander length and amplitude) may become smaller with a decrease in flood discharges, the slope, or the angle of entrance to the bend. Moreover, the experiments show that the more erodible are the banks, the wider and shallower will be the crossings between the bends to transport the greater load of sediment from the eroding banks. Because of the fact that the maintenance of channel cross sections and the movement of meanders must be accompanied by the movement of sediment, Benson and Thomas (1966) suggested that the dominant discharge with respect to meanders be defined as that discharge which over a long time period transports the most sediment. Though the highest sediment rates generally occur over a rather large range of flow rates, they found the dominant discharge defined in this manner to be much less than the bankfull stage discharge.

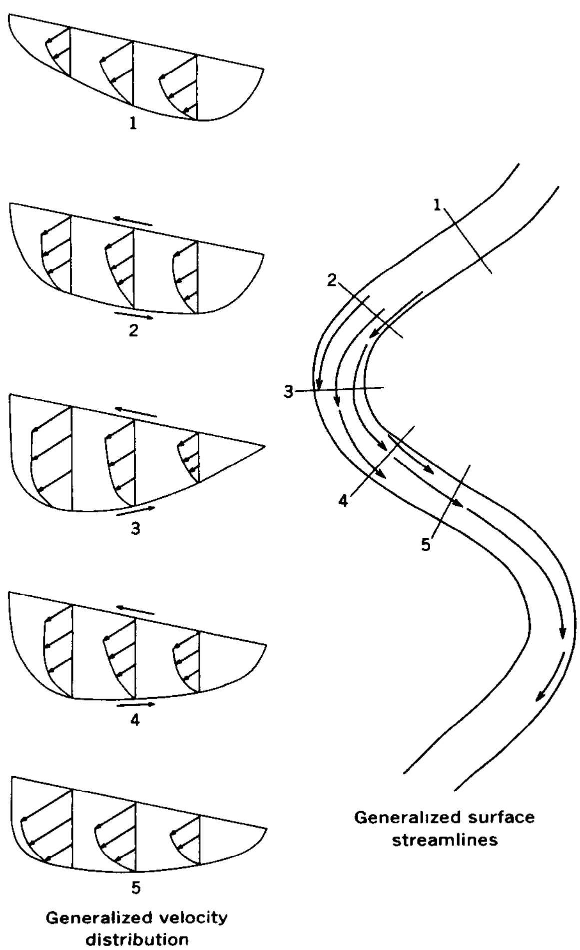


Figure 23.—Diagram of cross-sectional flow distribution in a meander. Note arrows indicating crosscurrents in sections 2, 3, and 4. Modified from Leopold, Wolman, and Miller (1964, p. 300).

The mechanics of meander and stream movement over a flood plain suggests that several features of sediment erosion and deposition may be observed. Some are more noticeable than others on a particular stream, depending on its sediment load and whether or not it is aggrading or degrading. Leopold, Wolman, and Miller (1964, p. 317) list the following features typical of the flood plain:

1. The river channel.
2. Oxbows or oxbow lakes, representing the cutoff portion of meander bends.
3. Point bars, loci of deposition on the convex side of river curves.
4. Meander scrolls, depressions and rises on the convex side of bends formed as the channel migrated laterally downvalley and toward the concave bank.
5. Sloughs, areas of dead water, formed both in meander-scroll depressions and along the valley walls as floodflows move directly downvalley, scouring adjacent to the valley walls.
6. Natural levees, raised berms or crests above the flood-plain surface adjacent to the channel, usually containing coarser materials deposited as floodflows over the top of the channel banks. These are most frequently found at the concave banks. Where most of the load in transit is fine-grained, natural levees may be absent or nearly imperceptible.
7. Backswamp deposits, overbank deposits of finer sediments deposited in slack water ponded between the natural levees and the valley wall or terrace riser.
8. Sand splays, deposits of flood debris usually of coarser sand particles in the form of splays or scattered debris.

In consideration of the geometric and sediment characteristics of the whole stream, it is apparent that a pattern of channel slope and cross section should exist that fits the "dominant" water discharge, the particle-size distribution, and the rate of sediment transport. A diagram (fig. 24) modified from Leopold and Maddock (1953, p. 27) shows how slope, roughness, sediment load, velocity, depth, width, and bed-material size vary with discharge at a station and downstream. Sections A and C represent headwater conditions of low and high flow respectively; B and D represent downstream conditions of low and high flow. Particle size of bed sediment should tend to decrease in the downstream direction and perhaps exhibit a slight increase with increasing flow rate at a site. Note that the indicated change in channel roughness is small in the downstream direction in spite of considerable reduction in skin resistance because of reduced particle size. Most of the reduced resistance from reduced particle size is counteracted by large-scale roughness in the form of increased meanders and (or) sand dunes.

The complexity of stream channels with respect to their shape and the way they may erode, transport, and deposit sediment is indicated in figure 25 (Culbertson and others, 1967). This figure is presented to further indicate the range commonly experienced concerning (*A*) the variability of unvegetated channel width, (*B*) sinuosity, (*C*) bank height, (*D*) natural levees, and (*E*) the modern flood plain.

Economic Aspects

The direct, and most certainly the indirect, economic significance of fluvial sediment problems is usually ignored because many fluvial sediment processes are related to, or are a part of, natural phenomena that often occur in an unnoticed manner. Hence, they are rarely considered for evaluation except when serious consequences can be easily noted and where corrective action is necessary. If the full impact of the erosion of sediment within the river drainage areas, the movement of sediment through stream channels, and the deposition of sediment along streams and in other bodies of water could be evaluated, the subject would be of much greater concern to society.

In a study of damages from sedimentation, Maddock (1969) notes that most information for erosion is presented in terms of loss of plant nutrients, the increased cost of tillage, channel degradation, and loss of land by shore and streambank erosion. For sediment deposits, the counterpart of erosion, most economic information involves maintenance and other costs from infertile material on flood plains, storage loss in reservoirs, channel aggradation, harbors filling, water-supply systems, hydropower turbines, transportation facilities, fish and oyster industries, and wildlife and recreation areas. Because of the subtle nature of sediment damages, this is but a small part of the total damage picture.

Not only may sediment damages go unnoticed, but often they are beyond economic evaluation and have considerable lasting social implication. Maddock states:

> Nevertheless, there are some land areas in the world, such as parts of the Near East and the limestone dolomite region of Yugoslavia, that have become a total loss, economically, during historic times. Nearer to home some agricultural areas of our southeast Coastal Plain have become practically useless through active erosion.

Gottschalk (1965) states:

> Most people have a natural antipathy of "muddy streams." This is particularly evident in fishermen. Aside from the fact that few people care to fish a muddy stream, there is a definite effect of suspended sediment on the size, population, and species of fish in a stream (Ellis, 1936). Suspended sediment affects the light penetration in water and thus reduces the growth of microscopic organisms on which insects and fish feed.

Though only a part of the economic aspects of sedimentation can be presented in terms of dollar damages, a list of several items (table 6) may be helpful to indicate the scope of the problem. As indicated by Ford (1953), it is virtually impossible to separate water damage caused by floods from that caused by a combination of water and sediment. For example, if a flood should cover a crop of wheat in the preharvest stage, the fine sediment in the water will likely impair maturity to a greater extent than if the flood consisted only of clean water. In

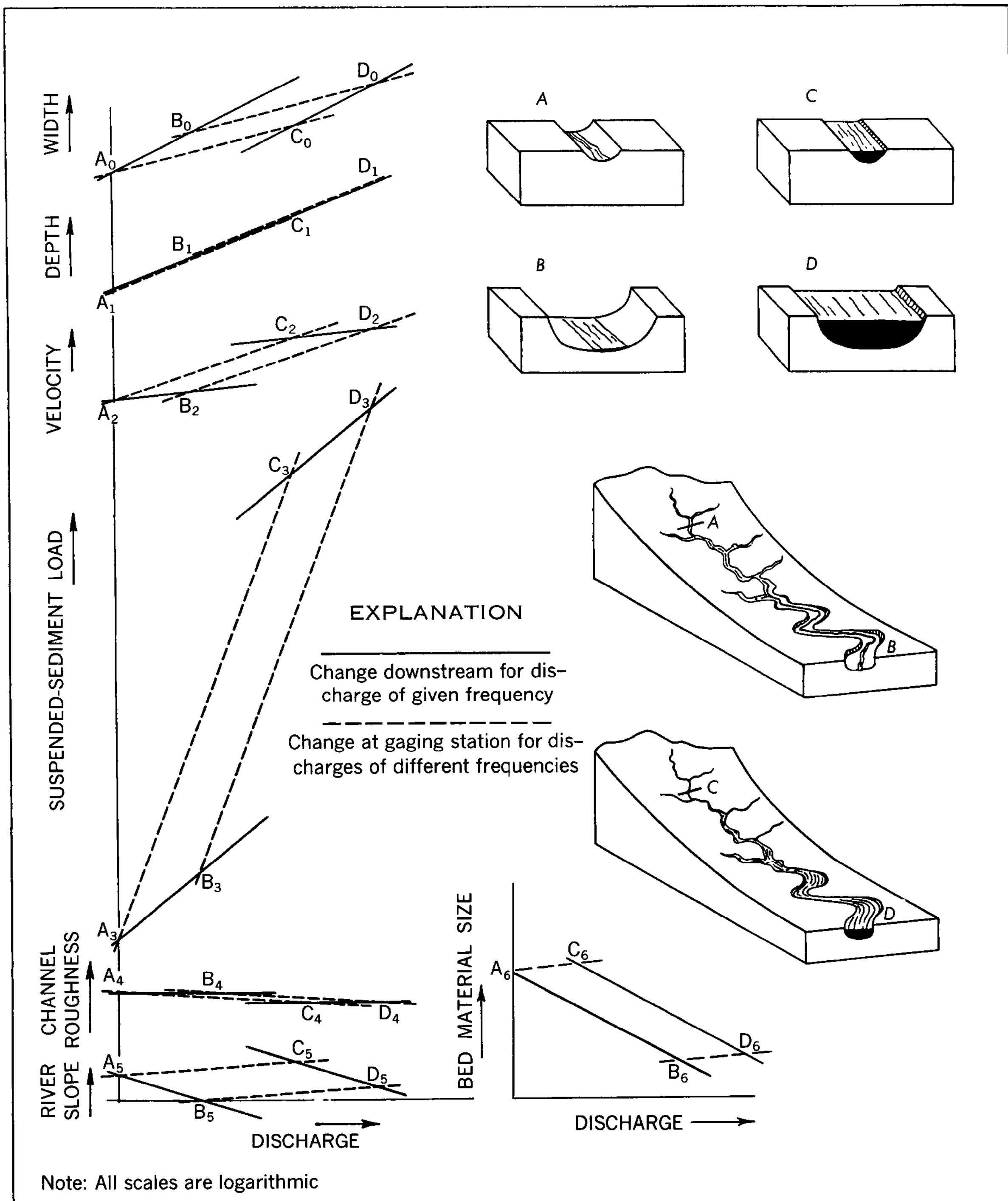


Figure 24.—Average hydraulic geometry of river channels by relations of width, depth, velocity, suspended-sediment load, roughness, slope, and bed-material size to discharge at a station and downstream. Modified from Leopold and Maddock (1953).

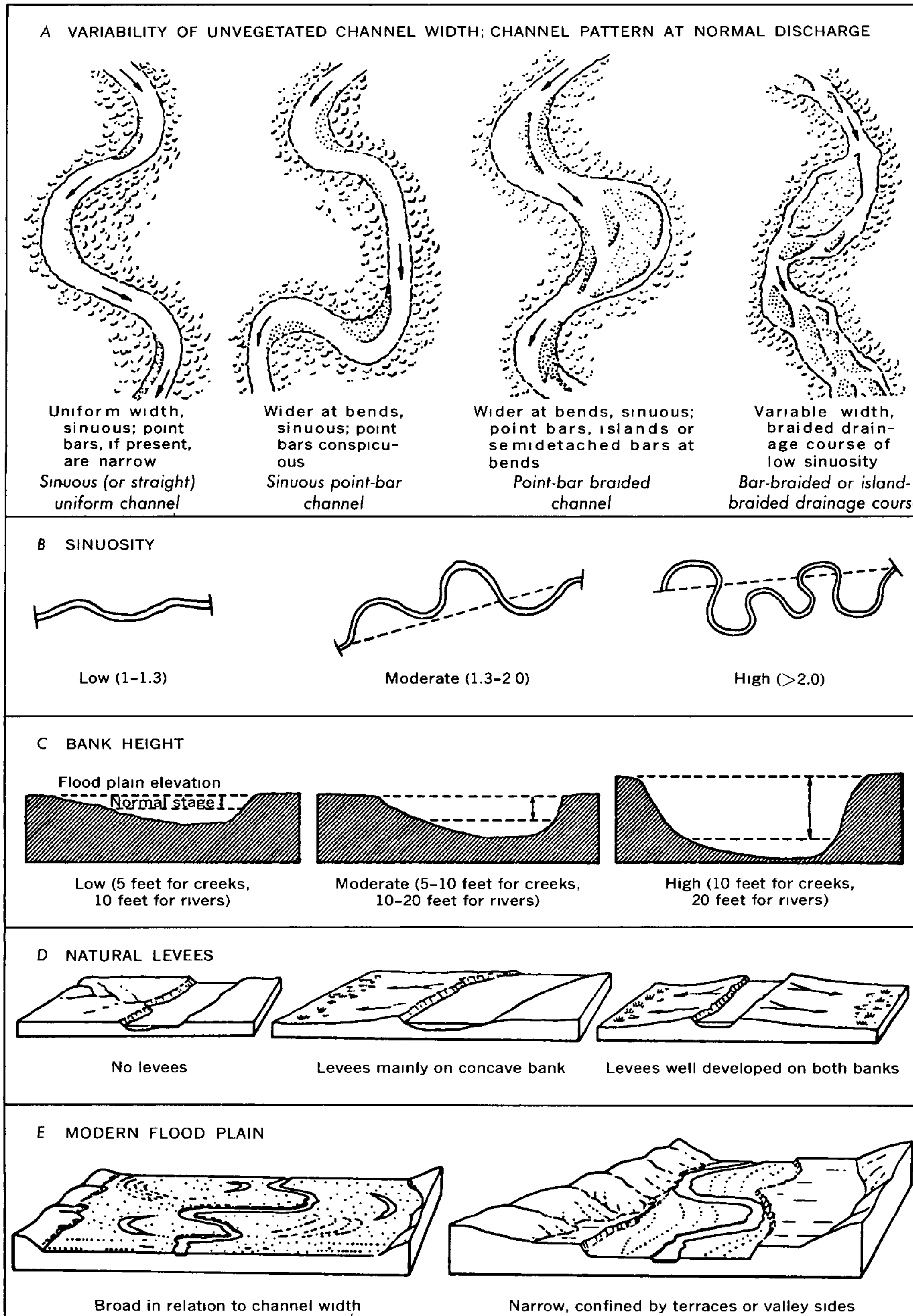


Figure 25.—Complexity of stream channels with respect to channel width, sinuosity, bank height, natural levees, and flood plain. Modified from Culbertson, Young, and Brice (1967, p. 48–49).

flooding of residential property, a large part of the flood damage, especially to household goods, is attributed to sediment in the water. Other types of sediment damage are more easily separated from pure flooding damage. The following broad groups of sediment damages are indicated by Ford: (1) infertile overwash, (2) swamping, (3) filling of reservoirs, (4) damage to water-infiltration facilities, (5) damage to transportation facilities, and (6) damage to drainage and irrigation facilities. Specific items from these groups can be noted in table 6.

Table 6.—Examples of damages from sedimentation

[Most items suggested from Maddock (1969). The damage is not given in dollars of uniform value]

Item	Amount	Basic reference
1. Increased crop production from use of applicable erosion control programs.	An average of $2.50 per acre of all cropland; many examples over $9.00.	Leopold and Maddock (1953).
2. Gully destruction of land in Iowa and Missouri.	Capitalized value to society of $603 per acre.	Weinberger (1965).
3. Decline in crop returns from sheet erosion on Austin clay soil in Texas.	Cumulated loss of $252 per acre as compared to uneroded areas.	Smith, Henderson, Cook, Adams, and Thompson (1967).
4. Infertile overwash, impairment of drainage, channel aggradation, flood-plain scour, and bank erosion.	$50,000,000 annually in United States based on survey of 34 basins representing one-eighth of land area.	Brown (1948).
5. Loss in storage reservoirs used for power, water supply, irrigation, flood control, navigation, recreation, and other multiple purposes.	$50,000,000 annually in United States based on surveys from 600 of the total of 10,000 existing reservoirs.	Brown (1948).
6. Maintenance and impairment of drainage ditches.	$128 for each of the 134,000 sq mi served by such ditches.	Brown (1948).
7. Maintenance of irrigation facilities	About 25 percent of annual total operation and maintenance charge.	Brown (1948).
8. Maintenance of harbors and navigable channels.	$12,000,000 annually (excludes deposits from tidal currents).	Brown (1948).
9. Water purification (excess turbidity)	$5,000,000 annually based on a sample of filter plants.	Brown (1948).
10. Damages during floods; deposits on crops, roads, streets, household effects, and increased flood heights.	$20,000,000 annually as a minimum or about 20 percent of the total flood damages.	Brown (1948).
11. Removal of debris from basins resulting from medium-sized storm in Los Angeles County, 1961.	1,235,000 cu yd at $0.85 (does not include the cost of other extras such as disposal sites).	Ferrell and Barr (1965).
12. Savannah Harbor, Ga.	More than $1,000,000 per year to cope with a shoaling rate of 7,000,000 cu yd per year.	Harris (1965).
13. Control of sediment movement at mouth of Columbia River.	Jetty construction $1,969,000 (1895), $9,972,000 (1917), and $6,000,000 (1941).	Lockett (1965).
14. Maintenance of beaches on coastal areas starved for sand by stream controls.	Expensive	Watts (1965).
15. Stabilization of Colorado River below Hoover Dam.	$30,000,000 exclusive of annual maintenance of structures.	Oliver (1965).
16. Reservoir space allotted to sediment storage for four dams on the middle Rio Grande.	$35,000,000 as a part of total cost of dams. Other "sediment" costs of projects not included.	Maddock (1969).
17. Channel erosion in Five Mile Creek near Riverton, Wyo., from effluent of Riverton irrigation project.	$400,000 plus $4,000 maintenance per year	Maddock (1960).
18. Erosion and transport from urban construction of about 5,000,000 acres in United States (mostly urbanization).	Depends on water and land use within and below construction sites.	Guy (1965), Wolman (1964).
19. Erosion and transport from rural cropland areas in United States since settlement.	Forced abandonment of crop production on 35,000,000 acreas.	U.S. Department Agriculture, Agricultural Research Service. (1965).
20. Estimated annual total erosion and sediment problems in United States.	$1,000,000,000	Moore and Smith (1968).

Data needs and program objectives

Data needs

No matter how precise the theoretical prediction of sedimentation processes becomes, it is inevitable that man's activities will increasingly cause the many variables to change relative to their effect on fluvial sediment. There will, therefore, be an increasing need for direct or indirect measurement of fluvial sediment movement and its characteristics to provide data for prediction of the kind and magnitude of sediment problems or to verify the usefulness of a given control measure.

Because of the changing effects of the environment on fluvial sediment, caused mostly by man's activities and the rapid advances in technology, it seems useless to list the many specific kinds of sediment problems we face today. Instead, it is desirable to list only the general areas of concern where many kinds of sediment problems have already occurred and where they may occur in the future.

Water utilization

Water-quality goals and objectives with respect to sediment are being set up with a view to specific domestic, industrial, recreational, and other water uses. Such goals should logically be subject to change as the requirements of use change. Esthetically, for example, a stream should be managed so that it will be more free of sediment when the use is changed from a "private" farming area to a park for public use. Thus, a knowledge of fluvial sediment conditions is needed to help establish criteria for water-quality standards and goals to aid in many aspects of water utilization.

It is difficult to assess the significance of turbidity or sediment concentration in water because of the many simultaneous interactions of detrimental and beneficial effects. Swimming and most recreational uses require nearly sediment-free water; on the other hand, turbid water will reduce or eliminate objectionable algal growth. Sediment is a problem at water-treatment plants because it requires an effort for its removal from the water and its disposal and yet some fine sediment is often desirable in order to effectively remove some organic and inorganic substances in the treatment process. Therefore, considerable monitoring is evidently needed, either in the form of daily or more frequent suspended-sediment measurements or perhaps in the form of a continuous assessment of turbidity as a hydrologic measurement. If turbidity measurement is accomplished, then additional conventional sediment measurements, at least on a periodic basis, will be required in most instances for effective evaluation with respect to water utilization.

Sorption and pollution concentration

The significance of sediment as a sorbing and concentrating agent of pollutants is not well understood with respect to many materials such as organics, pesticides, nutrients, and radionuclides. The organics associated with sediment are highly variable in quantity and tend to interact with many kinds of pollutants in a very complex manner. Because of the complex interaction with sediment, pollutant transport characteristics in streams must necessarily also be very complex. The relatively inert inorganic sediments are not so highly interactive with many pollutants, but they are known to be very important in some instances—two substances which readily affix themselves on sediment are the radionuclide cesium-137 from military weapons and phosphorus from water-treatment plants.

Variation of geomorphological settings

Much of the fluvial-sediment data in the past has been obtained on streams representing large areas of quite diverse environment. It is impossible to obtain data for all streams that have small drainage areas, but it should be possible to greatly increase knowledge concerning the environment-sediment relationship by careful selection of some representative basins for detailed study. If it is impractical to obtain detailed sediment information, it may be possible to use a systematic method of periodic sampling for a large number of basins for which the so-called "rating curve" of suspended-sediment concentration versus water discharge will serve as an empirical guide to environmental effects.

Logically, the reconnaissance type of data program should precede either the periodic or detailed study.

Work concerning the shape of alluvial channels and the erosion and deposition in streams in relation to sediment type and physical characteristics has only been started (Schumm, 1960, 1961). These early studies indicate that the silt-clay content in the channel and the banks affects the width-depth ratio of the stream. A channel composed of fine highly cohesive sediment may have new deposition of a durable nature on the banks as well as the channel floor. Rapid growth of vegetation in these fine sediments may aid such deposition, but it is not necessarily the initial cause of aggradation. If degradation occurs in the fine sediments, it is usually by upstream migration of headcuts. In contrast, a channel containing mostly sands has no deposition of durable deposits in the streambed and little or no "plastering" of fines on the banks. Vegetation is usually sparse on these poorly cohesive, highly mobile sediments. Bank caving is usually more active for the sand-bed stream than for the fine-sediment stream.

Leopold, Emmett, and Myrick (1966) measured the amount of sediment derived from different erosion processes in various physiographic positions in several ephemeral washes draining areas ranging from a few acres to 5 sq mi. The results showed that mass movement, gully-head extension, and channel enlargement are small contributors of sediment compared with sheet erosion on unrilled slopes.

Urban growth

Urban growth has several fluvial-sediment implications. In the construction areas, protective vegetation and topsoils are removed, and drainage areas, slopes, and channels are altered so that the environmental conditions are extremely dynamic with respect to area and time. After construction is complete, the surface erosional pattern may return to a condition somewhat better or worse than for the previous rural setting, but channel erosion will likely be accelerated because of the increased rate and amount of runoff resulting from increased imperviousness in the drainage basin. Although the total area involved with urban growth is small relative to the rural setting, it is worthy of considerable attention because of the dramatic increase in the intensity of sediment erosion, transportation, and deposition in comparison with the rural areas. Urban growth areas are representative of extreme sediment variation with time as well as space and therefore require intensive and detailed study.

Transport and deposition

Sediment transport and deposition processes form the connecting links between the initiation of movement by erosion and the resting place prior to consolidation. Fine-sediment transport occurs when particles finer than most found in the streambed are moved by small fluid forces in nearly continuous suspension. Coarse-sediment transport, on the other hand, occurs when those particles found abundantly in the streambed are moved intermittently by suspension and as bed load. The quantity of fines in the flow at a stream site depends on the release of these fines by erosion and their routing with the flow, whereas the quantity of coarse sediment moved depends on the availability of the specific sizes from the basin to maintain the stream boundary and the energy of the streamflow. Furthermore, the fine sediment tends to disperse with the fluid throughout the stream cross section, whereas the coarse sediment moves mostly near the bed of the stream and at a nonuniform rate across the width of the stream.

Channel aggradation or degradation will occur in a reach of a stream when the transport capacity of the flow does not match the supply of coarse sediment of specific sizes coming into the reach. Deposition problems may occur at any point in the flow system, beginning near areas of excessive erosion and continuing in manmade channels, in natural channels, in ponds and reservoirs, in estuaries, and on beaches. As indicated in several of the examples listed in table 6, the basic problem in connection with deposition is that it usually consists of an accumulation of unwanted material at a location desired for water storage or movement.

One important example relative to transport and deposition data needs concerns scour and fill with respect to structures in channels, particularly highway bridges. Prediction of scour or fill from hydraulic theory and empirical equations has proven uncertain, and hence, there is a great need for case histories to form a base for making better predictions. Culbertson, Young, and Brice (1967) indicate that scour and fill problems may be the result of (1) an increase in stream discharge, (2) an increase or decrease in sediment load relative to water discharge, (3) a change in local base level of the body of water into which the channel flows, (4) a change in channel slope, (5) a lateral shift or redirection of the channel, (6) a downstream progression of a sediment or debris wave, and (7) obstacles or constrictions in the path of flow. Their suggestions for the preparation of a case history on scour and fill include the assembly of such information as (1) photographs and maps, (2) aspects of construction and maintenance of the structure, (3) the morphological properties of the stream, (4) flood history, (5) cross-section and slope surveys, (6) velocity distributions for normal and high flows, (7) bed- and suspended-sediment discharge rates including particle-size distributions, and (8) the characteristics of bed forms including the depth of scour around piers and abutments.

Program objectives

In consideration of the many general problem areas in sedimentation, it is aximatic that program objectives, if they are quite specific, would have to be very flexible to meet the ever-changing set of problems. Unusually, however, a set of general objectives that are more stable can form the basis of the dynamic detailed objectives. An example of a set of these objectives was presented by R. B. Vice at Albuquerque in April 1967:

1. Develop and maintain a national network of sediment-measuring stations to provide unbiased comprehensive information about sediment movement in streams.
2. Study and describe sedimentation in specific priority areas so that water managers will have at hand essential information for choosing between alternatives.
3. Expand research studies in sedimentation to disclose and describe process relationships between water, sediment, and the environment.

Network and aerial coverage

Exclusive of special and local sediment problems, the World Meteorological Organization's "Guide to Hydrometeorological Practices" suggests a minimum design for a stream-sediment network to include 30 percent and 15 percent of the gaging stations in arid and humid regions, respectively. The extent of coverage for a specific budget is directly related to the unit cost, which in turn is a function of the size and complexity of the stream system and measurement site as well as a function of the kind and intensity of the sediment-sampling program. Data from sediment networks must provide a basis for the future prediction of events. Therefore, statistics relative to sediment movement and its related environment should include instantaneous and average characteristics as well as the range, variation, and patterns of fluctuations. Whetstone and Schloemer (1967) stress that "the value of data increases with quantity and quality, and therefore data should be systemically preserved." The availability of the electronic computer makes it feasible to reduce and codify data for effective storage and retrieval. The computer also makes possible more sophisticated approaches to hydrologic analysis.

Vice and Swenson (1965) state that a network is an orderly system for acquiring data. They further indicate that the fundamental elements of a network system should include (1) a distribution of stations where repetitive observations can be made that will describe the character and variability in time and space, (2) an evaluation of significant environmental features, (3) the evolvement of improved techniques of data collection, and (4) a continuing program for analysis and interpretation of available data to guide in refinement of the total system.

Present and future benefits in land and water management determine the optimum distribution of sediment data needed for a region. Thus a part of a region in the path of urban development must necessarily receive more intensive coverage than a part of the region set to a minor use. Vice and Swenson (1965) suggest that a beginning network can sometimes be approximated from existing sediment programs that have evolved in response to urgent water and sediment problems. They caution, though, that

> greater effort should be applied to (1) areas of abundant water supply, where large water use can be expected, (2) areas of high sediment variability, where more detail is needed, and (3) areas of high sediment concentration, where sediment is more likely to limit project feasibility.

Wallis and Anderson (1965) in a study of sediment yields from California drainage basins found that man's activities have increased sediment loads by 17 times, and therefore, "a well-designed sedimentation network must be flexible enough to allow for evaluation of the effect of changing land use."

Though the prediction of future events is probably the most important purpose to be served by a sediment network, the basic sediment network should often be supplemented by additional programs. These may be programed to provide detailed information on the location of erosion areas and the relative amount of the eroded material that is deposited at different locations within the basin. Special studies may also be required (1) to evaluate erosion-control programs applied to problem areas, (2) to determine the effects of interbasin water diversions, (3) to monitor sediment transport within and from areas of urban development, and (4) to evaluate the stress on urban channels from increased runoff.

Kinds of site records

The sediment-sampling program at a stream site can be considered to fall into one of three classes. The first is the continuous sediment record, usually called the daily station, in which the amount of sediment as measured by suspended-sediment samples is computed and recorded on a daily basis. A set of suspended-sediment samples should represent the sediment concentration of the stream at the time of the sample, and therefore, the data indicated by the sample must be extended backward and forward in time. The length of time applicable to a given sample depends on the time of the previous and next sample and whether or not there are important changes in stream conditions.

A good program for a daily station, then, requires not only the use of proper equipment to obtain good representative samples but also a very sophisticated set of instructions and judgment with respect to timing of samples. Such a program also depends on the major use of the data. If the problem considers mostly the needs of a water user withdrawing a relatively uniform amount, then the major emphasis should be on the sediment concentration of the flow, and thus the samples would be spaced rather uniformly in time. If the problem concerns the amount or tonnage of sediment moved by the stream, then it may be desirable to sample the low-flow periods once a week or on days of change and to sample two or three times a day during high-flow periods. The thunderstorm type of hydrograph is perhaps the most difficult to sample adequately because of the effects of uneven precipitation in the basin and because of the ever-changing environmental factors, many of which can be related to season of the year and to land use.

The second type of sediment-sampling program can be classified as a partial-record site. This is essentially the same as the daily record except that data are obtained only during selected times of the year based on a predictable period of high flow, or flow greater than a selected rate. The equipment used and the timing of samples for the partial record would be the same as for the daily record.

The third program is the periodic sediment record that may be represented by one of a large variety of sample techniques and timing. Perhaps the most common program would be the collection of samples for a sediment-discharge measurement each time a technician visits the station—once every 2 weeks or once a month, perhaps with more frequent observations during flood periods. These kinds of data provide information for publication of "instantaneous" values of water discharge, sediment concentration, and sediment discharge.

A series of reconnaissance measurements should usually be made prior to the establishment of any of the three programs to obtain comparative information on conditions likely to occur in the future. Even after a program is started, it should be expected that operational adjustments will be required with respect to equipment, sample timing, or even measurement location, especially in areas of changing land use.

Sometimes the requirements of any of these programs may be such that sediment must be measured in terms of total load, in which case it will be necessary either to sample the sediment at a site where it is suspended into the sampling zone by natural or artificial means, or to calculate the amount of the unmeasured sediment. As one would expect, any of the three programs requires a wide range of sampling arrangements determined by climate and drainage-basin characteristics, especially size. The data needs and the operation of a sediment-measuring station on the Missouri River at Kansas City, for example, are vastly different from the needs and operation of a station on a small channel draining a 10-acre basin in an area under urban development.

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