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RELATIONSHIPS BETWEEN MORPHOLOGY OF SMALL STREAMS AND SEDIMENT YIELD

By Task Committee on Relations Between Morphology of Small
Streams and Sediment Yield of the Committee
on Sedimentation of the Hydraulics Division

ABSTRACT: The state of the art in the relations between morphology of small streams and sediment yield is assessed. Research findings and recommendations for additional research are presented. Topics include systems and interactions, simulation models, channel forms and processes, transport of sediment in small streams, and aspects of channel morphology. Selected topics for additional research are also included.

INTRODUCTION

Stream channel morphology is literally the study of stream channel form and structure, but generally it is taken to mean their form and structure regarded as a whole or their collective morphological features. Because these features resul from deposition and erosion processes in the channel, which in turn are affected by the available sediment and its movement through the channel system, it is logical that we seek to know the controlling mechanisms between stream channe morphology and the associated sediment yield. For a given channel, total sediment discharge is the quantity of sediment moving past a cross-section of the channel in a given time interval (mass/time). The total sediment discharge relative to the contributing area or drainage area is the sediment yield (mass/area/time). Sediment discharge connotes a mass flux at a section relative to a contributing area. Therefore, in either case, it is necessary to quantify the sedimen discharge.

BACKGROUND

Relations between the morphology of small streams and sediment yield have been considered important for many decades, especially when changes in morphology might somehow be linked to changes in sediment yield from the landscape and its movement through the stream system. An excellent summary of the nature of sedimentation problems is presented in the ASCE *Sedimentation Engineering Manual* (ASCE, 1975). This manual describes problems of erosion

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related to geologic erosion, accelerated erosion, agricultural activities, urbanization, road and river control works, and water quality problems. Problems of sediment transport include movement of sediment, impingement of sediment particles, and sediment in suspension. Problems of sediment deposition include deposits at the base of eroding slopes, flood plain deposits, channel deposits, and deposits in lakes and reservoirs.

The Committee on Erosion and Sedimentation, American Geophysical Union (AGU) Hydrology Section published a report entitled, "Research Needs in Erosion and Sedimentation." This report stated (AGU, 1977, p. 1076):

> Erosion and sedimentation are important problems in environmental and water quality studies, watershed management, river mechanics and training, and dredging in waterways and harbors. The importance of these problems is being magnified by the increasing demands for energy and foods, which in turn require an increased water supply. Rivers are one of the key sources of water supply, but the river flow also contains sediments which create numerous problems. Thus, the water supply cannot be separated from erosion and sedimentation and related problems. In the United States, millions of Federal dollars are spent annually on research to deal with the problems of erosion and sedimentation. However, they are complex, and the present status of research is still very far from satisfactory.

Based on research needs identified by the ASCE Task Committees and by such groups as the AGU Committee on Erosion and Sedimentation, the ASCE Sedimentation Committee formed a new Taks Committee on Relations Between Morphology of Small Streams and Sediment Yield.

Objectives.—As published in the *Official Register* (1979), a purpose of the Sedimentation Committee is "to study and report on problems and solutions connected with the erosion, transportation, and deposition of sediment in urban waterways, rivers, canals, reservoirs, and harbors, including methods of sediment control." Under the Sedimentation Committee, the purpose of this task committee is:

1. To assemble and review information pertaining to stream morphology and its impact on sediment yield at different stream locations and preparation of a state-of-the-art report or paper to be published in the *Journal of the Hydraulics Division* with emphasis on the practical application of these techniques for predicting sediment yield in small streams.
2. To promote interchange of current research results on stream morphology and explore the feasibility of organizing a session on the subject matter for a future ASCE conference.
3. To identify problem areas and research needs in the area, and to advise funding agencies of these needs.

To meet these objectives, we have tried to limit our attention to small stream channels (as defined later) and to emphasize practical applications toward predicting sediment yield.

Scope and Limitations.—Definition of a small stream is subjective and difficult. The charge to this Task Committee specifically restricted attention to small streams while not defining the term. Schumm (1977) described an idealized fluvial system consisting of: Zone 1, the drainage basin as a sediment and runoff producer; Zone 2, the main river channels as a transfer component, and Zone 3, the alluvial fans, deltas, etc., as zones of deposition. However, Schumm (1977, p. 14) goes on to state, "Inherent in this idealized model is the assumption that one cannot divorce the events in the drainage basin (Zone 1) from the events in the channel downstream (Zone 2) and at the depositional sites (Zone 3). It is a true process-response system." At an early meeting of the Task Committee, an operational definition of a small stream was proposed as "one more directly affected by events in the upland area, and it is a part of the precipitation-flow complex."

A concept common to Schumm's Zone 1 and the Task Committee definition is that the small channel is an integral part of the runoff-sediment source area. As a part of the runoff-sediment source area, the small channel can be subject to erosion and, thus, produce sediment, but also, it can be an area of deposition, and, thus, a sediment sink. Therefore, for this report, we adopt an operational definition of a small stream or channel as a permanent feature of the landscape that conveys water and sediment from the upland areas to the major channels and acts as a sediment source or sink, depending upon the dynamic characteristics of the water-sediment flow system. Central to this definition is the sensitivity of the small channel to upland runoff and erosion processes and to hydraulic and sediment transport processes in the larger downstream channels.

Therefore, attention in this report is limited to small channels in particular. We seek to emphasize relations between morphology of these small channels and their associated sediment yield. To meet the objective of a state-of-the-art assessment, we limit attention to the published techniques and applications and do not seek to develop models or procedures independent of this assessment.

Several attempts have been made to categorize sedimentation problems (Simons and Senturk, 1977; Bogardi, 1978; and Shen, 1979) with the result that channel morphology and sediment yield are seen as components of complex systems representing several processes. Shen (1979) described these as: (1) Sediment supply from upland or contributing watershed area; (2) transport in channels; (3) dynamics of resistance and bed forms; (4) stream channel morphological relations; (5) sediment in coastal systems; and (6) sediment-pollution relationships. Simons and Senturk (1977) described the need for knowledge of: (1) Geologic factors; (2) hydrologic factors; (3) geometric features of the channels; (4) hydraulic factors; and (5) ecological and biological factors.

Therefore, to understand the relationships between channel morphology and sediment yield, it is necessary to understand how these, and perhaps other factors, interact to affect processes in the stream channels controlling morphology and sediment yield. While an explanation of these complex factors is beyond the scope of this report, we intend to review the most important interactions and provide limited source material for a more complete understanding.

SYSTEMS AND INTERACTIONS

As described in the introduction (Schumm, 1977; AGU, 1977; and others), the small stream channel is a component of a complex natural system and interacts with processes occurring in other components. Geomorphic and hydrologic features and processes of the drainage systems reflect processes in the runoff and sediment source areas (Schumm, 1977). Analysis of hydrologic processes providing input to the channel system requires: (1) Methods of predicting runoff; (2) methods of predicting upland erosion and sediment delivery to the channel system; and (3) development of the runoff hydrograph, including hydrologic and hydraulic routing, to consider erosion and sedimentation in the channel system. Items 1 and 3 are somewhat beyond the scope of this report, but will be examined briefly, with emphasis on item 2.

The U.S. Department of Agriculture (Agricultural Research Service (ARS), 1977) maintains a file of hydrologic models used in agricultural research, access to which can be obtained through the National Agricultural Library. The U.S. Forest Service (USFS, 1976) has prepared a state-of-the-art assessment of nonpoint water quality modeling, which includes discussions related to items 1 and 3. In addition to these sources for agricultural impacts, Brandstetter (1976) prepared an assessment of models used for storm sewers in urban areas. Brown, et al. (1974) made an assessment of methods for urban studies by the U.S. Army Corps of Engineers. Sources for mathematical models in hydrology include Clarke (1973), Fleming (1973), and World Meteorological Organization (WMO) (1975), wherein assessments are made of various simulation models in predicting runoff and streamflow, including hydrograph development. Indices of available computer programs for prediction of runoff are presented by Bowers, et al. (1972) and Chu and Bowers (1977). Methods for use of botanical evidence of floods and flood plain deposition are described by Sigafoos (1964). Finally, McCuen, et al. (1979) prepared a literature search and evaluated available techniques for flood frequency analysis on ungaged watersheds. These state-of-the-art assessments cited previously should provide an overview of current technology in runoff prediction and hydrograph development. The American Society of Agricultural Engineers (ASAE) Monograph (ASAE, 1981) on hydrologic modeling for small watersheds is a comprehensive source representing the state-of-the-art. Particularly appropriate material is contained in Chapter 4, "Infiltration and Percolation" (Skaggs, 1981), Chapter 5, "Surface Runoff, Storage, and Routing" (Huggins and Burney, 1981), and Chapter 13, "Currently Available Watershed Models," (Renard, Rawls, and Fogel, 1981).

Shen (1979) describes two approaches to investigation of soil erosion and sediment delivery to the channel systems. His first approach is the development of fundamental relationships between climatic factors, land use, soil characteristics, and hydraulics of overland flow and erosion and sediment yield. The second approach is in estimating sediment supply to the stream channels using regression equations.

Describing the first approach, Shen states, "Unfortunately, very little progress in the fundamental knowledge of this area has been made" (Shen, 1979, p. 1210). Overall, we feel this statement is correct, except that additional efforts underway have increased our knowledge of relationships between rainfall characteristics and erosion rates. This is not evident in the area of rainfall simulation to determine soil erosion. Bubenzer (1979) describes important characteristics for rainfall simulation, Meyer (1979) describes methods to attain these characteristics, and McCool (1979) relates rainfall simulator design criteria to regional differences in rainfall characteristics. Martinez, Lane, and Fogel (1979) related soil cover conditions to detachment of soil by raindrop impact, and Martinez (1979) conducted extensive field experiments on soil detachment by raindrop impact and overland flow using a rainfall simulator.

The most widely used erosion equation for upland areas is the Universal Soil Loss Equation (USLE), as described by Wischmeier and Smith (1965, 1978). Although the USLE is usually described as a regression equation, extensive research has been conducted to specify each of the factors under various conditions. For instance, the factors are standardized with respect to dimensions and fallow conditions on experimental plots. This leaves the rainfall energy factor to be obtained from rainfall data and the soil erodibility factor to be estimated as a "regression" coefficient or from soil characteristics (Wischmeier and Smith, 1978). A good general reference on soil erosion is provided by (SCSA) (1976). However, to estimate sediment yield from complex slopes or watersheds or to estimate sediment concentration throughout the hydrograph, additional modifications or developments are required.

Simulation Models for Erosion and Sediment Yield

A primary objective in developing simulation models for erosion and sediment yield is to link, and, thus, integrate through the dynamics of a routing procedure, the component processes affecting erosion and sediment yield. Although several approaches have been proposed (Knisel, 1980), due to similarities in the conceptual processes as sheet, rill, and channel erosion, many of the approaches have been similar. Knisel wrote (1980, p. 144), "Since water is the carrier of sediment and chemicals, most water quality models were developed by selecting a hydrologic model and 'piggybacking' sediment and chemistry components to produce a model package." Crawford and Donigan (1973) developed a model based on the Stanford Model (Crawford and Lindsley, 1962) using the sheet and rill erosion components of Negev's model (Negev, 1967). This procedure was described by Fleming (1975).

As part of an agricultural model for chemical transport, Frere, Onstad, and Holtan (1975) developed a modified USLE erosion/sediment yield simulation model. This USLE modification directly incorporates runoff erosivity to compute sediment transport and yield.

A system, or parametric model, based on the unit hydrograph principle was developed by Bruce, et al. (1975) and includes rill and interrill erosion concepts with sediment transport capacity determined by overland flow rates. This particular procedure may have applications under low gradient conditions characterized by hydrographs with long-durations or base-times.

Hjelmfelt, Piest, and Saxton (1975) developed partial solutions to the combined kinematic wave equations for overland flow and the upland erosion equations (Foster and Meyer, 1975) to derive erosion and sediment yield equations for upland areas. Shirley and Lane (1978) derived analytic solutions using the method of characteristics for the entire overland flow hydrograph. Their results extended the work of Hjelmfelt, Piest, and Saxton (1975) to include the entire overland flow hydrograph; by integrating the product of the runoff and sediment concentration solutions over the entire hydrograph, they obtained an event-based sediment yield equation.

Following equations presented by Bennett (1974), Smith (1976a) developed a distributed model for erosion and sediment yield on small watersheds. Smith used the kinematic flow equations, a sediment continuity equation, and empirical detachment and transport equations. By analyzing overland and channel processes as components, Smith simulated changes along the channel profile resulting from erosion and deposition. In a subsequent publication (Smith, 1976b), the model was tested using field data from a small semiarid watershed, and the importance of accurate hydrologic simulation in erosion prediction was demonstrated.

From the HEC-6 model (Hydrologic Engineering Center, 1977), which is also based on a sediment continuity equation, Pickup (1980) developed a large-scale model to estimate the sediment impacts resulting from a tropical dam project.

Beasley, et al. (1977) developed a distributed model to predict erosion and sediment yield for various agricultural management practices. Their procedure is based on a grid system whereby a watershed is represented by component processes at points on a grid. The erosion component is based on a modification of the USLE. Sediment transport capacity in overland and open-channel flow is computed with emphasis on deposition of sediment in stream channels.

Williams and Hann (1978) developed a model to compute erosion and sediment yield on agricultural watersheds. Their model included a modification of the USLE to include runoff volume and peak discharge rate. This model included application of linear programming techniques to select the best management practices based on nonpoint-source pollution criteria.

A comprehensive watershed or basin-scale model was developed at Colorado State University (Simons, Li, and Stevens, 1975; Simons and Li, 1976; Simons, Li, and Ward, 1977; Li, 1977; and Li, 1979). The kinematic-wave model is used for overland and open-channel flow routing, and the erosion component incorporates erosion by raindrop impact and overland flow. Bedload and suspended load transport rates are computed. Sediment routing in overland and open-channel flow include transport of various particle sizes. For this reason, the model has important applications in channel armoring and chemical-transport studies. Like the "Stanford Model," the "Colorado State Model" has been adopted for commercial applications and is, thus, receiving wide use.

A comprehensive field or small watershed, scale-model has been developed by the U.S. Department of Agriculture (Knisel, 1980; Foster et al., 1980; Knisel, 1980; Foster, Lane, and Knisel, 1980; Lane and Foster, 1980). This model incorporates fundamental principles of erosion, deposition, and sediment transport mechanics. Sediment detachment in overland flow is based on a modification of the USLE; transport capacity equations are used for overland and open-channel flow; channel erosion is based on excess shear stress, and deposition rates in impoundments are computed. Since this model includes detachment, transport, and deposition of sediment by particle-size fractions, it is especially suited for nonpoint pollution studies. Alternative agricultural management practices can be evaluated to determine their influence on sediment yield.

Although many of the aforementioned models include channel erosion and deposition, the processes occurring in stream channels are important enough and complex enough to justify a review of channel processes. As mentioned earlier, channel processes cannot be separated entirely from upland processes. However, enough of the processes occurring in channels are sufficiently important to justify further elaboration.

Channel Forms and Processes

The presence of a free surface in open-channel flow adds an element of complexity over closed-conduit flow in that the depth of flow is free to change in response to changing conditions. Flow in natural streams is characteristically unsteady and nonuniform. For the natural channels of interest here, the beds and banks have varying degrees of stability, but, for our purposes, are considered self-formed. Parker (1978, p. 109) summarized the problem for channels in noncohesive material as follows: "Rivers and canals with perimeters composed of noncohesive sand and silt have self-formed active beds and banks. Thus, they provide a most interesting fluid flow problem for which one must determine the container as well as the flow." These statements summarize an important aspect of the problem. The flow container, called the perimeter or channel bed and banks, is itself variable and dependent upon the flow conditions. As will be examined later, the same concepts hold for self-formed channels in cohesive material.

All characteristics of discharge (water and sediment) and channel geometry are interrelated; any change in one variable necessitates compensating change in one or more other variables. Thus, a change in sediment load, for instance, results in changes of channel width, depth, and gradient, which affect discharge, which in turn affects sediment load.

Alluvial Bed Forms.—The bed of a channel with water-sediment discharge can develop several forms. These bed forms in turn affect hydraulic resistance, and, thus, flow conditions. Although there has been considerable success in determining empirical relations between bed forms and flow characteristics (Mercer, 1971), success has not been as widespread in determining the physical mechanics of bed forms and related hydraulic resistance (Mercer, 1971; Shen, 1979). The importance of bed configuration in extreme cases has been emphasized by Simons and Richardson (1971); they note up to a three-fold change in resistance to flow and even more than a 10-fold change in concentration of bedload, depending on bed-form configuration.

Bed forms affecting alluvial channel roughness are summarized in a report by the ASCE Task Force on Bed Forms and Alluvial Channels (ASCE, 1966) wherein bed forms were divided into six classifications: ripples, bars, dunes, transition, flat bed, and antidunes. A regime approach was proposed by Simons, Richardson, and Haushild (1963), wherein bed forms were classified into lower-flow regime, transitional, and upper-flow regime. Various bed forms affecting channel roughness (after ASCE, 1966) are summarized in Table 1. The order in Table 1 is determined by the usual occurrence with increasing velocity and Froude number. Flow regime classification of bed forms corresponding with increasing average shear stress and associated characteristic values of the Froude number and Manning's n (after Simons and Richardson, 1971) are shown in the

TABLE 1.—Summary of Bed Form Configurations Affecting Alluvial Channel Roughness (ASCE, 1966) and Corresponding Regime Classification (Simons and Richardson, 1971)

Bed form (1)	Size of features (2)	Shape of features (3)	Comments: Behavior and occurrence (4)	Regime Classification		
				Regime (5)	Approximate Froude number (6)	Approximate n value (7)
Ripples	wavelength less than approx 0.3 m; height less than approx 0.03 m	roughly triangular in profile with gentle, slightly convex upstream slopes and downstream slopes nearly equal to the angle of repose, generally short-crested and three-dimensional	move downstream with velocity much less than flow velocity, generally do not occur in sediments coarser than about 0.6 mm	lower	0.14–0.37	0.018–0.030
Bars	lengths comparable to channel width; heights comparable to mean flow depth	profile similar to ripples; plan form variable	four types of bars are distinguished: point, alternating, transverse, and tributary, ripples may occur on upstream slopes	—	—	—
Dunes	wavelengths and height greater than ripples, but less than bars	similar to ripples	upstream slopes of dunes may be covered with ripples, dunes migrate downstream in manner similar to ripples	lower	0.28–0.65	0.020–0.040
Transition	vary widely	vary widely	heterogeneous array of bed forms, primarily low amplitude ripples and dunes interspersed with flat regions	transition	0.55–0.92	0.014–0.030
Flat bed	—	—	a surface devoid of bed forms, may not occur for some ranges of depth and sand size	upper	0.70–0.92	0.010–0.013
Antidunes	wave length approx $2\pi V^2/g$	nearly sinusoidal in profile, crest length comparable to wavelength	in phase with and strongly interact with gravity watersurface waves, may move upstream, downstream, or remain stationary, depending on properties, of flow and sediment	upper	>1.0 standing waves breaking waves chutes and pools	0.010–0.030 0.010–0.012 0.012–0.018 0.018–0.030

"Regime Classification" column in Table 1. Again, notice the range of possible n values corresponding with the bed forms.

Incorporating the discharge, channel geometry, and hydraulic resistance values, it is possible to develop predictions of depth-discharge relationships for alluvial channels. The "regime formulas" are summarized in the report of the ASCE Task Force on Friction Factors in Open Channels (ASCE, 1963). Einstein and Barbarossa (1952) analyzed depth-discharge relationships by including grain roughness and bed-form roughness. Their main contribution was in formally including the roughness influence of bed forms and developing the bar resistance curve (Einstein and Barbarossa, 1952, Fig. 3). Shen (1962) and Viega da Cunha (1967) extended the Einstein-Barbarossa method for particle sizes outside the sand-size range. Simons and Richardson (1966) and Haynie and Simons (1968) developed procedures to design stable channels in alluvium in the size range of 0.12–0.82 mm. Vanoni and Hwang (1967) investigated flow resistance from stablized ripple beds and related roughness to a length measure of the ripples. However, this length measure is, generally, unmeasurable in natural channels.

Shen (1975) analyzed the problems of interpreting skin and form resistance, and suggested analyses wherein prior assumptions of skin resistance for various bed forms are not based on resistance for a flat surface. The influence of temperature has been investigated by Shen, Mellema, and Harrison (1978), and Gee (1975) investigated forms in relation to unsteady flow. Nordin (1971), Willis (1976), and others have analyzed statistical properties of bed profiles in alluvial material that may suggest ways of relating these statistical properties to bed-form resistance. Bathurst (1978) investigated flow resistance of large-scale roughness elements and developed a resistance equation appropriate for them. He concluded that the roughness spacing can be defined in terms of the boulders protruding through the flow, but that additional work was needed to develop an equation suitable for engineering practices. Parker and Peterson (1980) have developed a depth-discharge predictor suitable for single-channel gravel-bed streams containing alternate bars. Finally, ASCE (1975, p. 145) presents a good analysis of the problems in applying the depth-discharge prediction equations.

Channel Forms.—The form of self-forming channels in the downstream direction is more in line with general geomorphic characteristics than the emphasis in the present section, but, inasmuch as channel form is interdependent with gradient and counter currents, it affects sediment transport capacity. Channels tend to be sinuous, and, certainly, thalwegs are usually sinuous (Leopold and Wolman, 1957; Lane, 1957), and these patterns are observed in flume studies (Brooks, 1958). General references for stream patterns include Leopold and Wolman (1960), Leopold and Maddock (1953), Schumm (1960), and Schumm (1963). Braided streams are usually found on steeper slopes (Lane, 1957; Leopold and Wolman, 1957; Osterkamp, 1978). Stream meander has been related to bank erosion (Friedkin, 1945) and to differences in shear stress on opposite banks (Shen and Einstein, 1964; Shen and Komura, 1968). Yang (1971) has explained stream meanders by minimizing the rate of energy expenditure. Callander (1969) has provided a comprehensive summary of stability theories of meandering, most of which treat alternate bars and do not require bank erosion as a necessary condition for meander inception. In any event, as noted by Schoklitsh (1930) and others since then, the natural stream channel, as a self-forming channel, meanders to adjust its gradient to the existing water discharge and sediment load. Further examination of these processes is given in ASCE (1975).

Transport of Sediment in Small Streams

Of necessity, an in-depth treatment of sediment transport mechanics is beyond the scope of this report. A general analysis of sediment motion, sediment transport classification, and sediment properties, including size, shape, and density affecting velocity, are summarized in Chapter II of the ASCE Sedimentation Engineering Manual (ASCE, 1975). Chapters 3–5 of Graf (1971) present hydrodynamics of fluid and sediment particle systems, including settling velocity of particles and viscosity. Chapters 6–14 of Graf (1971), in turn, present a summary of sediment transport in open-channel flow. Unfortunately, nearly all models and analyses of sediment transport involve only particles larger than 0.062 mm, and, thus, the effects of fine sediment are not generally included.

A comprehensive treatment of sediment transport in open-channel flow is given in a U.S. Department of Agriculture Technical Bulletin (Einstein, 1950) with reprints and additional publications listed by Shen (1972). Information on alluvial rivers was collected in a two-volume set by Shen (1971), and mechanics of open-channel flow and sediment transport were summarized by Simons and Senturk (1977). A basic source for hydraulics and sediment transport is the book, "Hydraulics of Sediment Transport" by Graf (1971). Bogardi (1978) presents an extensive treatment of sediment transport theory and results for alluvial streams, including a summary of suspended sediment transport research in the Soviet Union.

Evaluation of Selected Sediment Transport Formulas.—Selection of a sediment transport formula for a specific application might be based on any number of criteria, including simplicity, accuracy, and available data, depending upon user requirements. However, evaluations of this type are, of necessity, data-based. This becomes a serious limitation, especially when field data are used. Shen (1979, p. 1212) briefly examined this point.

> Although a great deal of research has been conducted on the total transport (bed load and suspended load) of cohesionless sediments by flow and many equations have been proposed, there is still not a generally accepted relationship available. A major difficulty is the lack of reliable field data in a zone close to the streambed, as it is generally agreed that bed load cannot be accurately measured by a bed-load sampler in large rivers if pronounced bed forms occur in the streambed. . .
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> The ratio of the measured suspended sediment load in the sampled zone to the total transport load is being actively debated. If one extends the vertical flow distribution and the suspended sediment concentration to the unmeasured zone and then uses the information to estimate the sediment load in the unmeasured zone, he will frequently find the unmeasured load in the unsampled zone can be 10–120% of the measured load in the sampled zone. This ratio is a function of flow and sediment characteristics, and, without knowing this ratio, one does not know the true sediment transport rate of a river, and thus cannot determine the accuracy of a transport equation. Of course, collecting field data is an extremely expensive and time-consuming job, and often no suitable site is available for the collection of usable data.

Therefore, the problems of choosing and evaluating a sediment transport formula are complicated, and, thus, analyses of the "best formula" are often academic. In this case, as in many others, "engineering judgment" must be used, and factors other than accuracy or best fit to available data become of increasing importance. Nonetheless, an example will illustrate the "accuracy" and "precision" of selected sediment transport formulas.

Example: Bed Load Transport in Open Channel Flow.—Alonso (1980) considered over 30 available sediment-transport formulas. Selection was based on the following criteria (Alonso, 1980, p. 426): "The selected formula should (1) Be framed so that it is easy to apply in computer simulation, (2) give the total load of bed material, knowing the hydraulic and geometric properties of the flow, and (3) provide reliable estimates when applied to channels of any size in which sediment particles are transported by the fluid." The eight formulas Alonso selected for analysis are shown in Table 2. To compare bedload prediction from the eight procedures, only sediment discharge of particles larger than 0.062 mm was considered. Data used to test the procedures were not used to calibrate the methods so that the results were indicative of predictive capabilities. Based on mean discrepancy ratios (calculated transport rates divided by observed transport rates) from 205 individual tests (Alonso, 1980, Table 3, p. 431), each procedure was ranked as shown in the last column of Table 2. As an example of the prediction accuracy, the overall mean discrepancy ratio for the 40 tests, using field data, was 1.06, representing a 6% overprediction. The mean discrepancy ratios varied from 0.24 for the MeyerPeter and Muller (1948) formula to 2.59 for the Yalin (1963) formula. The best overall predictor was

TABLE 2.—Summary of Selected Sediment Transport Formulas Evaluated by Alonso (1980)

Formula number (1)	Reference (2)	Type (3)	Comments (4)
1	Ackers and White (1973)	total load	rank[a] = 3
2	Engelund and Hansen (1967)	total load	rank = 4
3	Laursen (1958)	total load	rank = 2
4	MPME[b] (1948, 1950)	total load	rank = 6
5	Yang (1973)	total load	rank = 1, best overall predictions
6	Bagnold (1956)	bed load	rank = 5
7	MPM[c] (1948)	bed load	rank = 7
8	Yalin (1963)	bed load	rank = 8

[a] Based on mean discrepancy ratio (calculated over observed transport rate) from 40 tests using field data and 165 tests using flume data.

[b] MPME = Meyer-Peter and Muller (1948) formula for bed load and modified Einstein (1950) formula for suspended load.

[c] MPM = Meyer-Peter and Muller (1948) formula.

Yang's formula with a mean discrepancy ratio of 1.01.

From these results, Alonso (1980) concluded that the most reliable equation applicable over the entire range of flow conditions (very fine to coarse sands) was the formula proposed by Yang (1973). The formulas of Ackers and White (1973), Engelund and Hansen (1967), and Laursen (1958) were also judged reliable but produced relatively larger prediction errors. In view of Shen's comments, quoted earlier, these results are thought to be representative inasmuch as they reflect the magnitude of prediction errors likely to result in comparison with field data assumed to be correct. When we consider errors likely to be present in field data, these results probably underestimate the probable magnitude of the errors.

Example: Sediment Transport in Overland Flow.—An important consideration in extending sediment-transport equations to conditions encountered in very small channels and rills is how well the equations predict transport of particles with various densities representative of primary particles and soil aggregates. An extreme test is how well the equations perform in predicting sediment transport in overland flow. Foster, et al. (1980) used the Yalin (1963) equation modified to distribute transport capacity among the various particle types to compute transport capacity under experimental conditions on overland flow plots. They concluded that the modified Yalin equation gave reasonable results for transport of 0.156–0.342 mm coal and sand particles under laboratory conditions and for transport of Barnes loam eroded from field plots (Foster, et al., 1980, Table 3, p. 13). For these 13 experimental test results, the discrepancy ratio varied from 0.52–1.73 with a mean value of 1.09. Additional details on these experiments are given by Niebling and Foster (1980), and additional details on the modified Yalin equation are given in Foster and Meyer (1972), Davis (1978), and Khaleel, et al. (1980).

Summary and Analysis.—From the preceding examples, the material given in the references cited and the previous analyses, it is evident that a great deal of judgment is required in selecting a suitable sediment transport formula and interpreting the resulting predictions with respect to existing field data. The state-of-the-art in sediment transport theory and applications is such that it is not possible to select a "best" sediment-transport equation. Shen (1979, pp. 1212–1213) presents a brief outline of outstanding problems in our understanding of erosion, transport, and deposition of cohesive and noncohesive sediment.

As difficult as these problems are, and in spite of their complexity, significant advances in the relations between channel morphology and sediment yield have been, and are being, made. The next section briefly reviews some of these advances.

ASPECTS OF CHANNEL MORPHOLOGY

The form and structure of stream channels, i.e., their morphology, can be related to sediment yield because properties, such as average width, depth, slope, and shape adjust themselves to sequences of water discharges from the uplands, sequences of sediment discharges from the uplands and from their bed and banks, and to the properties of bed and bank sediments affecting erosion, transportation, and deposition. Even though the processes are complex and exhibit interdependencies, feedback, and seemingly random fluctuations, progress in engineering solutions suggests it is logical to simplify the processes to derive fundamental relationships. The resulting relationships will, of course, reflect the simplifying assumptions and represent averages or trends rather than specific deterministic solutions. The contention that this approach is justified, even at the expense of reduced predictive capability for specific applications, is supported by the assessment of the state-of-the-art in sediment-transport theory outlined in the previous sections of this report.

Regime Theory.—Regime theory has been developed from the need for design criteria for sediment-carrying canals. Canals that transported the flow without excessive amounts of scour or deposition were said to be in regime. The canals carrying water and sediment tended, at the specified discharge rates, to be in equilibrium, and, thus, stable. The basis of regime theory was the velocity-depth equation developed by Kennedy (1895). Subsequent developments concentrated on equations for width, depth, and slope in terms of water discharge and sediment characteristics.

In view of the many regime formula and publications describing them, no attempt will be made herein to review and interpret all of them. Rather, basic-source materials are compiled, a typical or representative listing of regime equations is tabulated, and relations between regime theory and hydraulic geometry are examined. With respect to this latter point, it should be noted that important differences between stable canals and natural streams include differences in the variability of discharge, straight versus meandering channels, and differences in sediment load.

Source Material for Regime Theory.—Regime formulas are summarized in an ASCE Task Report (ASCE, 1963), in appropriate text books (Henderson, 1966), in recent contributions from Colorado State University (Mahmood and Shen, 1971 and Simons and Senturk, 1977), and by Blench (1966). These references, together with important contributions by others, are listed in Table 3. The "comments" column in Table 3 lists some important aspects of regime theory examined in the cited references.

Representative Listing of Regime Equations.—A representative listing of regime equations for various channel types is shown in Table 4, with values of the coefficients and exponents given in Table 5. The first column in Table 4 lists the variable, the second column lists the regime equation, the third column lists the coefficient, and the fourth column lists the exponent for the regime equations directly involving the discharge, Q. The coefficients (K_1–K_4) for the regime equations vary according to the type of channel (Table 5), but, except for m, the exponent in the velocity equation, the exponents are assumed fixed.

From the regime equations listed in Table 4 (velocity and hydraulic resistance) and the variable exponent, m, shown in Table 5, the velocity, and, thus, hydraulic resistance, varies with hydraulic radius. Empirical and theoretical justification for the variable exponent is summarized by the bed-form roughness relations given in Table 1.

Reformulation of the Regime Equations.—Of the six equations shown in Table 4, the first two are expressed as power functions of the discharge. By incorporating continuity (discharge as the product of cross-sectional area and average velocity) and the algebraic identities listed in the footnotes of Tables 4

TABLE 3.—Summary of Selected References for Regime Theory

Reference (1)	Comments (2)
ASCE (1963)	report of ASCE Task Force; includes summary of regime formulas
Blench (1966)	analysis of regime theory, including application to rivers (Chapter 11) and history of regime theory (Chapter 6)
Blench (1969)	generalized regime equations by including heterogeneous bed and bank material
Bogardi (1978)	review of the regime theory, including historical development, summary of Simons and Albertson analysis and examination of new trends in regime theory
Henderson (1966)	summary of regime equations, example applications, and selected references, lists values of coefficients and exponents for various types of canals
Mahmood and Shen (1971)	summary of historical developments; presentation and analysis of Lacey's equations (Lacey, 1930, 1935, 1939, 1940, 1947, and 1958); reviews relation to hydraulic geometry and reviews various analyses of regime equations; authors' observations include applications and interpretations
Simons and Albertson (1960, 1963)	classification of types of canal bed and banks, listing of regime equation deficiencies, values of coefficients and exponents, and graphical relations
Simmons and Senturk (1977)	chapter 7 includes examination of empirical formulas for stable channel design, listing of Lacey's silt factors, and example applications

and 5, it is possible to reformulate the regime equations in terms of the discharge. These equations (in the original English units) are shown in Table 6. Here, the hydraulic resistance is expressed in terms of the Manning n value, and the average width of the channel is used. The last two columns of Table 6 show the coefficients, a_i, and exponents, b_i, for the power functions of discharge. Based on the original coefficients and exponents shown in Table 5, values of a_i and b_i for the discharge power functions are shown in Table 7. Notice that the exponents in Table 7 are dependent upon the assumed values of 0.5 for the wetted perimeter and 0.36 for the hydraulic radius, as listed in Table 4. They are also dependent on the assumed values for m, as shown in Table 5. If other values for these exponents had been assumed, then the exponents shown in Table 7 would also be different.

These comments and the reformulation of the regime equations facilitate comparison of the regime equations with the equations referred to as hydraulic geometry.

Hydraulic Geometry.—Hydraulic geometry consists of a set of equations representing relationships between width, depth, velocity of flow, and a characteristic discharge in open-channel flow (Leopold and Maddock, 1953). The similarity with regime theory is obvious, but there are essential differences. Although regime theory is applied to natural streams, the previously cited differences between stable canals and natural streams (i.e., differences in variability of discharge, channel alinement, and sediment load) are important. Moreover, Leopold and Maddock (1953) used discharge of equal frequency which, as a result, increases in the downstream direction. The resulting relationships between channel morphology and discharge of constant frequency but increasing in the downstream direction results in power functions of the type represented in Table 6. Studies of channel geometry are similar to those of hydraulic geometry, but differ by relying on measurements of channel width and depth (rather than water width and depth) taken from an identifiable geomorphic reference level. Unless otherwise specified, the term hydraulic geometry is used here for both types of equations.

Representative Listing of Hydraulic Geometry.—Based on the work of

TABLE 4.—Representative Listing of Regime Equations for Various Types of Canals (Simons and Albertson, 1960, as Modified by Henderson, 1966)

Variable (1)	Equation (2)	Discharge coefficient (3)	Discharge exponent (4)
Wetted perimeter, P	$P = K_1 Q^{0.5}$	K_1	0.5
Hydraulic radius, R	$R = K_2 Q^{0.36}$	K_2	0.36
Average width, b	$b = 0.9\ P$	—[a]	0.5
	$b = 0.92\ B - 0.2$	—	—
Average depth, y	$y = 1.21\ R,\ R \leq 7$ ft	—	0.36
	$y = 2.0 + 0.93\ R,\ R > 7$ ft	—	0.36
Average velocity, v	$v = K_3\ (R^2 S)^m$	—	—[a]
Hydraulic resistance, C^2/g	$C^2/g = v^2/gyS = K_4(vb/\nu)^{0.37}$	—	—

[a] Discharge coefficient and exponent determined implicitly after P, R, b, B, and y are determined, which by continuity, determines v. The final step is to compute s given the equation for average velocity or the hydraulic resistance equation in which C = the Chezy coefficient; B = the top width for the given cross section. The cross-section area is $A = b\ y = PR$.

Note: English units are used in these equations.

TABLE 5.—Values of the Coefficients and Exponents Used in the Regime Equations Shown in Table 4 (Simons and Albertson, 1960, as Modified by Henderson, 1966)

Coefficient or exponent[a] (1)	Type of Canal Bed and Banks				
	Type 1 sand bed and banks (2)	Type 2 sand bed and cohesive banks (3)	Type 3 cohesive bed and banks (4)	Type 4 coarse noncohesive material (5)	Type 5 same as Type 2 with heavy sediment loads (6)
K_1	3.5	2.6	2.2	1.75	1.7
K_2	0.52	0.44	0.37	0.23	0.34
K_3	13.9	16.0	—	17.9	16.0
K_4	0.33	0.54	0.87	—	—
m	0.33	0.33	—	0.29	0.29

[a] See Table 4 for definitions. Note that wetted perimeter P varies as $Q^{0.5}$ and hydraulic radius varies as $Q^{0.36}$. Since cross-sectional area $A = PR$, by continuity average velocity v varies as $Q^{0.14}$.

Note: English units are used in these equations.

Leopold and Maddock (1953), the equations comprising hydraulic geometry are summarized in Table 8. Notice that the discharge exponents in Table 8 are in close agreement with corresponding exponents from the regime equations (Table 6), but there is an additional relation between suspended sediment load and discharge.

Subsequent analyses derived hydraulic geometry for streams and rivers, and empirical evidence suggested that the exponents exhibited regional variation (Table 9). The most significant differences between exponents for regime theory (Table 7) and hydraulic geometry (Table 9) are for the slope and roughness exponents (b_4 and b_5 in Table 7, and z and y in Table 9). In synthesizing the prediction equations from these two historical sources, it is necessary to examine these differences and to determine their origin and implication.

As will be shown later, some of these differences can be explained in terms of hydraulics and sediment-transport theory. However, major differences were mentioned by Osterkamp (1980). For instance, Osterkamp (1980) found that

TABLE 6.—Reformulation of the Regime Equations Shown in Table 4 as Functions of Discharge for a Rectangular Channel[a]

Variable (1)	Equation (2)	Discharge coefficient (3)	Discharge exponent (4)
Average width $W = a_1Q^{b_1}$	$W = K_1/1.21\ Q^{0.5}$	$K_1/1.21$	0.5
Average depth $y = a_2Q^{b_2}$	$y = 1.21\ k_2\ Q^{0.36}$	$1.21\ K_2$	0.36
Average velocity $v = a_3Q^{b_3}$	$v = 1/K_1K_2\ Q^{0.14}$	$1/K_1K_2$	0.14
Slope $S = a_4Q^{b_4}$	$S = (1/K_1K_2^{m+1}\ K_3)^{1/m}\ Q^{0.14/m-0.72}$	$(1/K_1K_2^{m+1}\ K_3)^{1/m}$	$0.14/m - 0.72$
Roughness $n = a_5Q^{b_5}$	$n = [1.64\ K_1K_2^{5/3}/(K_2K_2^{m+1}\ K_3)^{1/2m}]\ Q^{0.07/m-0.26}$	$1.64\ K_1K_2^{5/3}/(K_1K_2^{m+1}\ K_3)^{1/2m}$	$0.07/m - 0.26$

[a] Computations for $R \leq 7$ ft and average width equal to cross-sectional area divided by average depth.

Note: English units are used.

TABLE 7.—Values of the Coefficients and Exponents of Discharge in the Reformulated Regime Equations Shown in Table 6 Based on the Original Coefficients and Exponents Shown in Table 5

Coefficient or exponent (1)	Type of Canal Bed and Banks: Type 1 sand bed and banks (2)	Type 2 sand bed and cohesive banks (3)	Type 3 cohesive bed and banks (4)	Type 4 coarse noncohesive material (5)	Type 5 same as Type 2 with heavy sediment loads (6)
Width					
a_1	2.89	2.17	1.81	1.44	1.41
b_1	0.5	0.5	0.5	0.5	0.5
Depth					
a_2	0.63	0.53	0.45	0.28	0.41
b_2	0.36	0.36	0.36	0.36	0.36
Velocity					
a_3	0.55	0.87	1.23	2.48	1.73
b_3	0.14	0.14	0.14	0.14	0.14
Slope					
a_4	0.000207	0.000771	—	0.0209	0.00404
b_4	−0.30	−0.30	—	−0.24	−0.24
Roughness					
a_5	0.0278	0.0301	—	0.0358	0.0293
b_5	−0.05	−0.05	—	−0.02	−0.02

Note: English units are used.

TABLE 8.—Summary of Hydraulic Geometry Equations for Rivers in the Downstream Direction (Leopold and Maddock, 1953)

Variable (1)	Equation (2)	Discharge coefficient (3)	Discharge exponent (4)
Average width	$w = aQ^b$	variable	0.5
Average depth	$d = cQ^f$	variable	0.4
Average velocity	$v = kQ^m$	variable	0.1
Slope[a]	$s = tQ^z$	—	—
Roughness[a]	$n = rQ^y$	—	—
Suspended sediment load	$L = pQ^j$	variable	0.8

[a] Explicit treatment of slope and roughness given in subsequent publications (Leopold, Wolman, and Miller, 1964).

TABLE 9.—Regional Values of Hydraulic Geometry Exponents for Bankfull or Mean Annual Flow in the Downstream Direction (Leopold, Wolman, and Miller, 1964)

Region and data source (1)	Hydraulic Geometry Exponents Defined in Table 8: Width, b (2)	Depth, f (3)	Velocity, m (4)	Slope, z (5)	Roughness, y (6)	Suspended sediment, j (7)
Midwestern U.S., average values	0.5	0.4	0.1	−0.49	—	0.8
Pennsylvania Brandywine Creek	0.42	0.45	0.05[a]	−1.07	−0.28	—
Semiarid U.S. ephemeral streams	0.5	0.3	0.2	−0.95[b]	−0.3[b]	1.3
Eastern U.S. Appalachian streams	0.55	0.36	0.09	—	—	—
Minimum variance solution[c]	0.53	0.37	0.10	−0.73	−0.22	0.8[d]

[a] Solution does not satisfy continuity since $b + f + m \neq 1.0$.

[b] Data from ephemeral streams in New Mexico suggest $z = -0.23$ and $y = -0.14$. Experimental data from rills developing in cohesive soil suggest $z = 0.0$, and $y = -0.16$ (Lane and Foster, 1980).

[c] Solution obtained by minimizing sum of squares of the exponents.

[d] Computed value based on $m/f = 0.27$ and $b = 0.53$ from Fig. 18, p. 25, of Leopold and Maddock (1953).

exponents of the width-discharge equation increase with recurrence interval, because flood peaks are attenuated in the downstream direction. Moreover, flood discharges are not as well defined as more frequent (e.g., mean discharge) discharge rates. Channel width and the exponent in the width-discharge equation tend to increase with increasing variability of discharge. An important point is that width-discharge relations (as well as other hydraulic geometry equations) in natural channels are not constant through time, but, in fact, respond to the ensemble of discharge rates experienced by the channel. Other factors being equal, stream channels more closely approximate equilibrium conditions when the discharge is less variable, as in regulated streams and canals. Finally, there is the problem of defining channel width. Typically, and traditionally, width has been defined as "bank-full" or "whole-channel" corresponding to discharges with recurrence intervals on the order of two years (e.g., 1.5- to 2.33-yr floods, annual series, for perennial streams, and even longer return period floods for ephemeral streams). However, an active channel width as a within-channel feature was defined by Hedman, Kastner, and Hejl (1974). The active-channel was described by Riggs (1978, p. 89) as: "The upper limit of this section (the width) is a within-channel dimension represented by: (1) The width of the low-water channel, (2) the distance between the within-channel bars (higher than the lowest prominent bed feature), or (3) the distance between annual vegetation lines." Following a similar definition for active-channel width, Osterkamp (1980) related mean discharge to channel width with less variation in the power relations than found when using larger floods of longer return periods.

Taken as a whole, it is not surprising that greater variability in water and sediment discharge, greater variability in channel patterns, increased errors associated with definition of a characteristic discharge, and more difficulty in defining channel dimensions produce differences in the exponents found in hydraulic geometry (Table 9) and regime theory (Table 7).

Selected references for hydraulic geometry are shown in Table 10. The first column of Table 10 lists the reference, and the second column presents comments as to content and relation to regime theory. The references cited in Table 10 present an empirical body of evidence for hydraulic geometry under a wide range of conditions beyond the summary presented in Table 9, and represent an even wider range in the exponents. Although the empirical evidence clearly shows that the power-function relationships known as hydraulic geometry apply under many circumstances, sufficient uncertainty in the values of the coefficients and exponents remains to prevent application of the procedures to predict the relationships between channel morphology, discharge, and sediment yield. The state-of-the-art in hydraulic or channel geometry is that the equations can be used if they are first calibrated with data from a given channel system. However, this need for calibration limits their power to predict relationships on ungaged channel systems. The next section examines selected attempts to relate coefficients and exponents in hydraulic geometry to physical features of the channel systems.

Extension of the Hydraulic Geometry Concepts.—Examination of the literature suggested that there are three main approaches to extension of hydraulic geometry using physical features of the channel systems. In the first approach, parameters of the hydraulic geometry equations are related to features of the channel systems by classifying the channels according to features of the bed and

banks with representative values of the parameters determined for each classification. The second approach is to assume a sediment transport relationship and derive hydraulic geometry given the transport relationship and the flow hydraulics at equilibrium. The third approach is to assume an erosion equation and derive

TABLE 10.—Summary of Selected References for Hydraulic Geometry

Reference (1)	Comments (2)
Blench (1957, 1969)	formulation of regime theory
Chitale (1966)	data from stable channels in India
Dury (1973)	examination of frequency analyses
Emmett (1972)	
Emmett (1975)	
Engelund and Hansen (1967)	monograph for sediment transport, including relation to hydraulic geometry
Gupta (1975)	analysis of large floods
Hack (1957, 1973)	stream-profile analysis
Hack and Young (1959)	meander and stream-channel profiles
Harvey (1975)	
Heede (1972a, 1972b)	mountain streams
Inglis (1947)	analysis, includes meander patterns
Inglis and Allen (1957)	
Kennedy (1895)	introduction of regime theory
Lacey (1930, 1934, 1947, 1958)	series of papers presenting regime theory
Lane (1937, 1955)	investigations and analysis of design of stable channels
Langbein (1964, 1965)	
Langbein and Leopold (1964)	concepts of quali-equilibrium in channel morphology
Lapturev (1969)	computational procedures for stable canal beds
Leopold and Maddock (1953)	presentation of hydraulic geometry, basic source for development and interpretation of equations
Leopold, Wolman, and Miller (1964)	textbook summarizing much of the previous work by the authors, including minimum variance solution for the exponents
Li (1974)	aspects of channel morphology related to a simulation model, including upland processes
Maddock (1969)	analysis of straight channels
Mahmood and Shen (1971)	comprehensive summary and discussion
Orme and Bailey (1970)	influence of management on channel geometry
Richards (1973, 1976)	review of channel roughness and complex relationships in streams
Simons and Albertson (1960)	formulation of regime theory (Tables 4 and 5)
Smith (1974)	derivation of hydraulic geometry
Wilcock (1971)	relationships between bed load transport and channel geometry
Williams (1978)	minimum variance theory
Wolman and Brush (1961)	laboratory study of channels in noncohesive material

hydraulic geometry given the erosion equation and the flow hydraulics as equilibrium is approached.

The first approach includes such classifications of the type shown in Table 5 (Simons and Albertson, 1960; Henderson, 1966), wherein parameters are specified for various types of channels characterized by type of sediment in the channel bed and banks. Schumm (1960) also classified the shape of alluvial channels according to sediment characteristics and included the amount of silt-clay in the channel as a variable in regression equations for hydraulic geometry. This work, together with related analysis, is presented by Schumm (1971). In a series of publications (Osterkamp, 1977; Osterkamp and Hedman, 1977; Osterkamp, 1978; Osterkamp, 1979; and Osterkamp, 1980), a classification system, based on sediment properties of channel bed and banks and channel pattern, was developed and channel geometry parameters derived based on a large number of streams.

Channel classifications, sediment characteristics, and hydraulic geometry exponents, based on the references cited previously, are shown in Table 11. Notice that the width-discharge coefficients vary by a factor of three, and the exponents vary by a factor of two. However, except for the braided sand channels, the slope exponent is nearly constant and comparable to the values for the regime equations. Subsequent analysis may provide similar classifications for the remaining hydraulic geometry exponents. In any event, these examples represent the methods of determination of hydraulic geometry parameters by classification and regression analysis based on characteristics of the bed and bank material.

In the second approach, a sediment transport relation is generally assumed to describe sediment load. Given a particular discharge, when sediment load equals sediment transport capacity, then the channel is at equilibrium, and the resulting channel geometry defines hydraulic geometry. Chien (1956) assumed Lacey's wetted perimeter-discharge equation with an exponent of 0.5 and Einstein's bed-load function (Einstein, 1950), and reproduced the regime equations for particular ranges of bed-load transport. Henderson (1963) also derived regime equations based on channel stability criteria and the Einstein sediment-transport formula. Gill (1968) also derived regime-type equations using Einstein's bed-load formula. Parker (1979) and Chang (1980) have derived such forms for gravel-bed streams. The result of many such derivations (Ackers and Charlton, 1971) is that the coefficients and exponents in the regime equations and hydraulic geometry were shown to be functions of sediment characteristics as well as discharge. Similar derivations using other sediment transport equations suggest that the parameters are also determined by the particular sediment-transport formula assumed.

A basic problem in this approach (as in the others) is that the degrees of freedom for a self-adjusting channel are generally greater than the number of pertinent equations one can impose. For instance, a channel can adjust its width, depth, velocity, roughness, and slope. It can also adjust its channel patterns, such as sinuosity, through meandering and flow patterns through braiding. Roughness or hydraulic resistance has been shown to be variable, depending upon flow and sediment conditions. Einstein, Anderson, and Johnson (1940) and Einstein and Chien (1953) found that the relation between suspended load and instantaneous bed material composition are complex. Generally, the continuity equation, a flow resistance equation, and a bed-load sediment transport equation can determine three degrees of freedom, leaving at least two undetermined.

TABLE 11.—Summary of Osterkamp's Channel Classification and Derived Hydraulic Geometry Parameters—Derivations Assume Active-Channel Width and Mean Discharge

		Hydraulic Geometry Parameters		
		Width, $w = aQ^b$		Slope, $s = tQ^z$
Classification (1)	Sediment characteristics (2)	Coefficient, a (3)	Exponent, b (4)	Exponent, z (5)
High silt-clay bed	bed: >60% silt-clay	5.1	0.47	−0.25
Medium silt-clay bed	bed: 31–60% silt-clay	7.0	0.57	−0.25
Low silt-clay bed	bed: 11–30% silt-clay	7.5	0.58	−0.25
Sand bed, silt banks	bed: <11% silt-clay, $d_{50} < 2.0$ mm[a] banks: >70% silt-clay	8.4	0.59	−0.25
Sand bed, sand banks	bed: <11% silt-clay, $d_{50} < 2.0$ mm banks: <70% silt-clay	9.0	0.62	−0.25
Sand bed, sand banks, braided	bed: <11% silt-clay, $d_{50} < 2.0$ mm banks: <70% silt-clay	3.0	1.0	0.0 to −0.25
Gravel bed	bed: gravel, $2.0 \leq d_{50} \leq 64$ mm	8.0	0.55	−0.25
Cobble bed	bed: cobble, $64 \leq d_{50} \leq 256$ mm	7.5	0.54	−0.25
Boulder bed	bed: boulders, $d_{50} > 2.56$ mm	7.7	0.51	−0.25

[a] Median particle size, d_{50}.

Note: Units are in the SI System.

This problem of indeterminancy was approached by Langbein (1964), Langbein and Leopold (1964), and Leopold and Langbein (1963) using arguments of equal power expenditure per unit of bed area and equal power expenditure per unit of channel length. They concluded a unique solution is not possible, but instead suggested a most probable state existed to produce an approximate solution. Yang (1976) suggested that sand-bed channels adjusted their hydraulic geometry consistent with developing minimum unit stream power. However, it is not clear exactly which formulation of stream power is to be minimized, and questions exist as to the physical justification for minimization.

Nearly all regime formulas for channel width are empirical. An analytical approach for the channel width was suggested by Chang and Hill (1976) using the concept of minimum stream power.

Chang (1979) used a sediment transport formula (DuBoys and Einstein-Brown), a flow resistance relationship, and a minimum stream power relationship to compute equilibrium geometry of sand-bed rivers. Regime rivers were classified in three regions of a discharge-slope graph, with one region corresponding to gentle slopes and flow resistance in the lower flow regime. Regime canals are representative of this classification. Region 2 is a transition between Regions 1 and 3, with steep slopes. It would be interesting to examine consequences of flow in Chang's three regions and their interaction with increasing discharge in the downstream direction.

Hey (1978) presented conditions under which natural channels have nine degrees of freedom because of their ability to adjust hydraulic geometry, plan shape, and bed forms. Hey suggests that knowledge of the processes is insufficient to use them to define flow and hydraulic geometry of rivers, and suggests multiple regression using field data. Presumably, the result would be a classification scheme, as described earlier, with some physical reasoning for the classification and for the coefficients and exponents of the hydraulic geometry in each class.

The third approach assumes an erosion equation, and then hydraulic geometry is specified as the flow hydraulics and erosion rate approach equilibrium. The primary difference between this approach and the sediment transport approach is in the assumption of controlling processes. In the erosion approach, flow tends to scour the bed and banks until the geometry is adjusted to a balance between erosive forces and the ability of the material to resist erosion. Thus, equilibrium is established. In the sediment transport approach, flow characteristics, and, thus, sediment transport capacity, are adjusted to match available sediment load, and equilibrium is again established. Of course, detachment and deposition of sediment occurs in natural channels, and thus, both approaches appear reasonable. However, it may be that the erosion approach is more appropriate for high flow rates and steep channels in cohesive material where detachment capacity, rather than transport capacity, limits the processes tending toward equilibrium; the sediment transport approach may be more appropriate under conditions other than these.

The erosion approach was used by Foster, et al. (1980), Lane and Foster (1980), and Rohlf and Meadows (1980). Based on flow conditions, such as an assumed cross-sectional geometry, an assumed distribution of shear stress in the cross section, and an excess shear equation for detachment rates, Foster, et al. (1980) and Lane and Foster (1980) derived relations describing hydraulic geometry for small channels in cohesive material. The basic problems with their approach were: (1) The cross-sectional shape determines, and in turn is determined by, the assumed shear-stress distribution; and (2) values of soil erodibility and critical shear stress are difficult to determine for cohesive soils. Rohlf and Meadows (1980) combined a similar approach with sediment transport using Einstein's method to examine erosion rates in an experimental rill system (see Foster, et al., 1980). Their simulated erosion rates generally underestimated Foster's measured values, and the resulting channel widths tended to be less than the observed widths. The reason for these discrepancies may be that, under actual field conditions, sediment yield was limited by detachment capacity rather than transport capacity, which exceeded sediment load (Lane and Foster, 1980). Also, it may be that their assumed shear-stress distribution did not "flatten" enough with increasing width-depth ratio as the eroding channel widened.

What remains to be done in synthesizing the erosion and sediment transport approaches is the development of criteria to determine under what conditions the two approaches are most appropriate. This may require the computation of detachment and transport capacity throughout a hydrograph as the discharge varies in time. Similar calculations may be required along a channel profile as the discharge is, indeed, spatially varied in natural streams. The beginnings of this approach have been formulated (Foster, et al., 1980) where excess shear is used to compute sediment detachment capacity in eroding channels, and a sediment-transport equation is then applied to compute transport capacity. Depending upon the flow conditions in spatially varied flow, sediment yield is then controlled by detachment capacity or transport capacity given the existing sediment load as a function of time and space. The results appear promising for small streams in agricultural soils, but extension to natural rivers awaits development of a usable hydrologic model to provide upland inputs of water and sediment as well as realistic estimates of flow hydraulics in larger channels.

SUMMARY

The main objective of this paper is to assemble and review information on stream morphology and its impact on sediment yield at different locations in small streams. Toward this end, a definition of small streams was adopted, and it was shown that the small stream must be seen as a component of the water-sediment flow system. It is logical that such a water-sediment flow system is greatly dependent upon complex interactions with the upland areas. Larger downstream channels may sometimes affect some aspects of small-stream systems.

Simulation models for erosion and sediment yield were reviewed, and their role in providing estimates of the upland inputs of water and sediment to stream channels was reviewed. Many of the models include channel erosion and deposition. However, the processes occurring in stream channels are complex and possess sufficient problems of interest to justify separate consideration while acknowledging that they are not independent of upland processes described by the simulation models.

The presence of a free-water surface in open-channel flow adds an element of complexity in that the depth of flow is free to change in response to changing conditions. Flow in natural streams is characteristically unsteady and nonuniform. Moreover, the beds and banks of natural channels have varying degrees of stability and are seen as self-formed. At any point in the stream system, and at any particular time, the channel geometry determines the hydraulics of the flow system. The flow system, in turn, interacts with the bed and banks, as well as the sediment load, to determine the channel geometry. Thus, the system is characterized as self-formed, with complex interactions and feedback.

Alluvial bed forms and their relation to hydraulic resistance, and, thus, depth-discharge formulas, were reviewed and were found to be of various forms dependent on flow conditions. Bed forms can be classified into lower, transition, and upper flow regimes as related to flow characteristics, such as Froude number and Manning resistance coefficients.

Self-forming streams in the downstream direction can be patterned as straight, meandering, or braided. The patterns and associated temporal and spatial interactions are again seen as complex inasmuch as channel form can affect the gradient and countercurrents, and thus, channel geometry and sediment-transport capacity. Channels tend to be sinuous, especially the thalwegs, and these patterns can also be seen in flume studies. As a simple example, a channel can meander to adjust itself to existing water and sediment discharge and valley gradient to achieve the required channel gradient.

Sediment-transport formulas were reviewed; their applicability and accuracy under field conditions were studied, and examples of evaluations were presented. The problems of choosing and evaluating a sediment-transport formula are complicated, and, thus, discussions of the "best formula" are often academic. Under these circumstances, engineering judgment must be used, and factors other than accuracy or best fit to specific data sets become of increasing importance.

The form and structure of stream channels (their collective morphological features or their morphology) are related to sediment yield. This is because properties, such as average width, depth, velocity, slope, and shape, adjust themselves to sequences of water discharges from the uplands, sequences of sediment discharges from the uplands and from their bed and banks, and to the properties of bed and bank sediments affecting erosion, transportation, and deposition. Because processes are complex and involve interdependencies, feedback, and seemingly random fluctuations, progress in engineering solutions suggests that it is logical to use simplified models of the processes to derive fundamental relationships. The resulting relationships reflect the simplifying assumptions and generally represent averages or trends more than specific solutions. The assertion that this approach is justified, even at the expense of reduced predictive capability for specific applications, is supported by the assessments of the state-of-the-art in predicting the upland inputs to channel systems and in sediment-transport theory.

Regime theory developed from the need for design criteria for sediment carrying canals. Canals which transported the flow without excessive amounts of scour or deposition were said to be in regime. Hydraulic geometry describes similar relationships for rivers in regime or dynamic equilibrium. The state-of-the-art in regime theory is such that sufficient criteria can usually be derived for the design of stable canals. However, the state-of-the-art in hydraulic geometry for natural streams is such that the equations can be used if they are first calibrated with data from a given channel system. This need for calibration limits their power to predict relationships on ungaged streams where data for calibration are unavailable.

To overcome the need for calibration of hydraulic geometry equations for natural streams, attempts are being made to extend the hydraulic geometry equations. These methods generally fall into three categories: (1) Classification methods where characteristics of the channel bed and banks are used to separate stream channels into classes with representative values of the parameters determined for each classification; (2) sediment transport methods where a transport relationship is assumed and hydraulic geometry is derived using flow hydraulics and sediment transport at equilibrium; and (3) erosion methods where an erosion equation is assumed and hydraulic geometry is derived given the erosion relationship and flow hydraulics as equilibrium is approached. To date, the most successful approach has been the classification method because of the dependency of the other two methods on the form of the sediment transport or erosion equation assumed together with the other assumptions, such as minimum stream power, required to derive a solution.

The most promising method appears to be a synthesis of the erosion and sediment transport methods wherein excess shear is used to compute detachment capacity in eroding channels, and a sediment-transport equation is then applied to compute transport capacity. Depending upon the flow conditions in unsteady and spatially varied flows, sediment yield is then controlled by detachment capacity or transport capacity, given the existing sediment load as a function of time and space computed at the previous time and position. This method holds promise for cohesive as well as noncohesive material with unsteady and spatially varied flow as occurs in natural streams. The main conceptual limitation to this synthesis of erosion and sediment transport methods appears to be a lack of understanding of accretion processes tending to narrow or "heal" a channel following a large flow event.

The effects of geologic materials in a regional sense are not well-documented, though they have been noted by Graf (1979) as explaining some of the observed variation in hydraulic geometry. Geologic materials directly affect channel shape by means of erodibility, and indirectly affect sediment loadings and characteristics through weathering products.

Bank vegetation affects the processes of channel erosion and sedimentation by introducing roughness and increasing the stability of bank materials. Hadley (1961), Zimmerman, et al. (1967), Smith (1976), and Graf (1978) have documented this interaction, but further work is required on the role of vegetation in increasing flow resistance and bank stability.

Natural stream channels, unlike canals and flumes, are sometimes actually low-water conveyance routes and, during the greatest discharges of water and sediment, much of the conveyance may be over the floodplain. In small watersheds, the floodplain may be several times the width of the stream, and the "channel" may assume much different proportions during a flood. Floodplain surfaces, usually being vegetated, tend to offer much more hydraulic resistance. Depth of flow is also much less over the floodplain than in the channel. Thus, despite the much greater width of the floodplain relative to the channel, the floodplain conveys a much smaller proportion of the water discharge than the relative widths might suggest. Likewise, sediment transport capacity may be reduced. In such a manner, much of the sediment load from the uplands can be lost to storage in the floodplain. This is one reason why, in many streams, sediment yield per unit area tends to decrease downstream.

SELECTED TOPICS FOR ADDITIONAL RESEARCH

Research is needed to identify, describe, quantify, and develop prediction equations for hydrologic and geomorphic features and processes of the drainage system or watershed as they represent the runoff and sediment source areas and the mechanisms of delivery to the channel system. These topics include both the development and features of channel systems, and the influence of geologic, vegetative, climatic, and other controls. Also of interest are regularities and randomness in drainage networks and accuracy of predictions based on statistical relationships including relations between drainage-net runoff and sediment yield. Analyses of hydrologic processes providing input to the channel system should include: (1) Methods of predicting runoff; (2) state-of-the-art in predicting upland erosion and sediment delivery to the channels; (3) quantitative definition of the manner in which sediment is stored as channel and floodplain material; and (4) development of the runoff hydrograph including hydrologic and hydraulic routing. Included in hydraulic routing is the need for simplified and accurate procedures to route streamflow accounting for the influence of contractions, backwater, drawdown, and other localized effects known to be important in scour and sediment transport.

To better estimate delivery of sediment to the channel systems, improved procedures are needed to compute detachment and transport, including deposition, in shallow flow in noncohesive material including soil aggregates. This is necessary to overcome the problems of assuming an empirical relation, such as delivery ratio. Research in the entire area of detachment, transport, and deposition of particles of various degrees of cohesiveness, various size ranges, and densities associated with biological and chemical processes is needed for upland areas contributing runoff and sediment supply to channel systems. Research is also needed to determine parameters for the Universal Soil Loss Equation under a broad range of nonagricultural land uses and to modify or improve it where necessary.

Comprehensive guidelines for selection and application of appropriate sediment-transport formula for use in natural stream channels do not exist. There is an urgent need to test the proposed transport formulas under a variety of conditions likely to be encountered in engineering practice. A systematic analysis of the assumptions required for each formula and for the range of conditions where each formula is applicable is needed. Of major importance would be a listing of conditions under which each formula should not be applied, either because these conditions violate the stated assumptions of the formula, or because the formula is known to yield unrealistic estimates under the given conditions. Such guidelines would at least narrow the range of options available to the engineer and, perhaps, aid in developing improved relationships. Since efforts to relate channel morphology and sediment yield must either use a sediment transport relation or rely on the implications of an assumed relation, the lack of a suitable sediment transport formula tends to limit progress in developing physically based relationships between channel morphology and sediment yield. Also, the lack of a suitable sediment-transport relation for natural streams makes interpretation of empirical relationships tenuous and dependent on the assumptions required for each sediment-transport formula. If the assumptions are not met in the natural stream, then interpretations often have little relationship to actual processes occurring.

Research is needed in the areas of detachment, transport, and deposition of cohesive sediments, including soil aggregates. Research is needed on erosion resistance of cohesive sediments as related to physical structure and physiochemical attraction. When particles are detached as aggregates, their size ranges are far different from the primary particles, and densities vary widely in comparison to sand-gravel particles of similar sizes, resulting in differences in transport and deposition rates. Moreover, information on aggregate stability is needed as the particles travel in the downstream direction. This is particularly important in determining sediment supply from the upland areas.

Additional research in sediment transport should emphasize transport of sediments of all size ranges, particularly sizes outside the sand-size range. Information is needed on interactions of particles of various sizes on the total transport rate. Clearly, not all the fine particles are eroded before coarser particles begin to be transported, and, in deposition, not all coarse particles are deposited before fines begin to be deposited. Differential rates of detachment, transport, and deposition of particles of various sizes, including suspended-bed load interactions, need to be better understood for incorporation in practical transport equations.

Techniques to determine the influence and significance of secondary currents on bed configuration and sediment transport are needed to consider three-dimensional flow in natural streams. Since three-dimensional flow patterns affect velocity distributions and lateral transfer of water and sediment, they may be significant in channel morphology-sediment yield relationships.

Because the stable or equilibrium channel represents a tendency toward a probable state; because it may be more philosophically, esthetically, and economically acceptable to man; and because it may be more amenable to classification, it is of primary concern. However, knowledge of departures from steady state is important to understand and to predict the response of streams to natural and man-influenced changes. For this reason, research is needed on dynamic behavior of natural streams. This provides justification for research on unsteady and spatially varied flow in three-dimensional channel systems. To understand and predict departures from equilibrium, it will be necessary to understand nonsteady state behavior.

Research is needed to synthesize information from channel morphology and processes to relate channel morphology and sediment yield in stable channels. There is a need for definition of basic relationships and necessary simplifications required to develop prediction techniques. Information is needed on the influence of channel patterns on sediment-transport rates and channel stability. Relations between channel patterns, channel geometry, sediment, soil, geologic, vegetative factors, and discharge are needed to aid in developing channel stabilization and control criteria.

The relation of sediment yield to stream-basin morphology is not fully developed and is a potentially promising topic for research. Work in the past has generally been of a statistical nature, and relations evolved were usually specific to a particular region.

An important basin variable has been drainage area. The relationship generally found has been that sediment yield declines with increasing drainage area. Two general explanations have been offered for this increasing area-decreasing sediment yield phenomenon. The first is the upland theory as exemplified by Boyce (1975), who contends that the explanation lies in the fact that average slope in a basin generally declines with increasing area, and, thus, less erosion per unit area occurs in larger basins. A contrasting view is held by Gottschaltz and Jones (1955) and Guy (1970) who contend that the increasing area-decreasing sediment yield relationship is based in large part, on data from agriculturally impacted basins where much eroded material has been stored. Trimble (1975, 1976, 1977) supports this view and further contends that much of the increasing area-decreasing sediment yield phenomenon may be only transitory.

As stated earlier, the state-of-the-art in hydraulic geometry is that, generally, the procedures cannot be used without calibration to predict relations between channel morphology and sediment yield. Research is needed to synthesize the classification, sediment transport, and erosion methods to relate coefficients and exponents in the hydraulic geometry equation to physical features of the channel systems, and, thereby, develop reliable equations to predict channel morphology-sediment yield relations.

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