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Overview: Channel morphology and sediment transport in steepland streams

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ABSTRACT New understanding of how steepland channels are formed is being pursued over a large range of scales, from entrainment of bed particles to the transfer of stored sediment down channel systems. Low submergence of bed particles during transport and wide heterogeneity in particle sizes strongly affect bedload transport. At the scale of a reach, scour-lobes are becoming widely recognized as common constructional units governing behavior of braided, meandering, and pool-riffle channels. Channel morphology and sediment transport can be radically altered by infrequent debris flows and torrents, however, which provide a common linkage between mass movement on hillslopes and sediment transport in channels. Because of the impracticality of monitoring the downstream progress of sediment over meaningful periods, sediment routing is best approached by mathematical models that incorporate the age and volume of sediment in storage reservoirs.

INTRODUCTION

Steepland channels differ from lowland channels in ways that fundamentally affect their behavior. Interest in steepland channels is accelerating as conflicts proliferate over human settlement, water development, timber harvesting, fisheries, mining, preservation of wilderness, and natural hazards. This interest is demonstrated by several recent symposia on special topics of steepland channels, such as debris flows, volcanic hazards, gravel-bed rivers, and sediment routing.

One of the most attractive aspects of the study of steepland channels is the great range in time and space with which problems can and should be addressed. The papers in this chapter mark some important advances over the entire gamut of scales, beginning with the initial motion of individual particles and ending with the transfer of entire sediment loads down channel systems over millenia.

BEDLOAD TRANSPORT

Effect of low submergence of bed particles

For a given size distribution of bed material, relative submergence at the entrainment threshold, d_c/D, is less for channels with steeper slopes (d_c is the critical depth of particle entrainment, and D is a representative particle diameter). Entrainment thresholds, relations between friction and roughness, and flow regime expressed by Froude number begin to change as d_c/D becomes less than about 15,or channel slope exceeds about 0.5 to 2%.

Most of the changes in the hydraulic conditions for bedload transport mentioned earlier arise from effects of large bed particles on the vertical distribution of velocity. In this respect, Bathurst (1978) defined three domains of relative submergence: (A) Bed roughness is small-scale if d/D exceeds 15, and one can apply relations between friction and roughness that treat bed particles collectively as a source of frictional shear and disregard the flow below the tops of particles. (B) At an intermediate scale ($4<d/D<15$), these relations no longer apply because a substantial portion of the flow is below the tops of protruding particles. Velocities are much lower and velocity gradients are less steep in this region than in the flow above. Rising wakes of low-velocity water are shed by protruding particles and further reduce velocity. As a result, friction is greater and the shear stress available to entrain bed particles is less than predicted by equations for channels with small-scale roughness (Ashida & Bayazit, 1973). (C) Large-scale roughness elements ($d/D<4$) individually affect flow and sediment transport in complex ways that depend on their shape, spacing and location (Bathurst, 1978).

Steep channel gradients further affect bedload transport by causing local supercritical flow and hydraulic jumps. Although widespread supercritical flow in natural channels is rare, it can be frequent in the vicinity of large bed particles in steep, coarse-bedded channels (Peterson & Mohanty, 1960). Hydraulic jumps associated with local supercritical flow can affect forces acting on particles and greatly increase flow friction. At steeper slopes, hydraulic jumps occur behind smaller particles, and thus friction is greater for a given relative submergence.

Measurement of bedload transport rates in steep channels that might be used to validate new equations have only been done successfully in laboratory flumes. Mizuyama (1977) demonstrated that the increase in friction for high relative roughnesses reduces transport efficiency. Wiberg and Smith's (1985) general model for saltation can apply to rolling and sliding of large particles at low excess shear stress and, in this volume, they introduce modifications for size gradation and fluid forces at low submergence and high Froude number.

Transport of hetereogeneous particle sizes

The wide range in particle sizes in steep channels further complicates bedload transport. The high exposure of large particles and the hiding of small particles may cause heterogeneous sizes to have nearly equal mobility (Parker & Klingeman, 1982; Andrews, 1983). A wide range in particle sizes may reduce the mobility of mean sizes (see also, Mizuyama, 1977). Sand in small proportions, however, can increase gravel transport by creating locally smooth areas over which gravel is rapidly transported (Iseya & Ikeya, in press). At low submergence, the relative mobility of small particles in a heterogeneous bed can be enhanced (Mizuyama, 1977). This may enhance sediment sorting in steep channels and cause small bedload particles to be rapidly transferred. to gentler reaches. Bathurst (this volume) suggests using critical discharge to decipher the effect of size gradation on selective entrainment in boulder-bed channels.

Debris flows and torrents

Debris flows and torrents have such large and long-lasting effects on channels that fluvial processes during intervening periods may play only a secondary role in shaping channel features. Important advances have been made recently in understanding debris flows and their effects on channels (these proceedings). Debris torrents -- debris floods, or debris flows that incorporate woody debris from forested catchments (Swanston & Swanson, 1976) -- have received less attention (Benda, 1985). Recognition of the signatures and probable travel distances of debris flows and torrent can be vital in interpreting the history of channel morphology and sediment transport.

Two-phase flows transporting large volumes or hyperconcentrations of sediment that are derived from debris flows may affect steepland channels more commonly than debris flows by themselves. Debris flows commonly come to rest in fairly steep channels [slopes no less than about 3 to 5% (Takahashi et al. 1981; Ikeya, 1981)]. Debris flows can mix with the water in the channels they enter, however, become diluted, and continue downstream as two-phase flows over gradients of a few percent or lower (Pierson & Scott, 1985). Hyperconcentrated, two-phase flows can also be produced by post-depositional reworking of debris flows (Mizuyama & Uehara (1983). In the Pacific Northwest of North America, outside of areas around active volcanos, widened channels and clast-supported deposits signifying single events of voluminous bedload transport are much more common than deep, narrow channels and matrix-supported deposits signifying debris flows. There are few theoretical models, laboratory experiments, or field studies to specify how sediment is transported and deposited in two-phase flow events carrying voluminous coarse bedload with or without woody debris and how these flows affect channel morphology.

CHANNEL MORPHOLOGY

Bed particles in steep channels can become organized in a wide range of particle groupings from armor layers, gravel clusters (Laronne & Carson, 1976; Brayshaw et al., 1983) and transverse ribs or step-pools (Whittaker & Jaeggi, 1982) to larger scale features such as bars and braids (Ashmore, this volume). These forms affect particle entrainment, transport paths, and frictional losses and constitute some of the basic features of channel morphology.

Bed forms in steep channels

Sheets Sheets are migrating accumulations of bedload one to two grain-diameters thick that alternate between fine and coarse particles (Whiting & Dietrich, 1985; Iseya & Ikeda, in press). They form in mixed beds of gravel and sand that contain up to 50% sand (Iseya & Ikeda, in press). Sheets are formed when moving sand and gravel segregate into alternating mobile zones of low grain roughness (sand areas) and high grain roughness (gravel areas). Gravel moves rapidly across smooth areas of sand and congregates abruptly downstream where other gravel particles create high grain-to-grain friction. Discontinuous and unpredictable assemblage, movement, and deposition of sheets cause high variation in gravel transport and confound attempts to relate transport to hydraulic variables. The role of grain roughness in sheet formation suggests that it may also be an important factor in deposition over larger channel features.

Particle clusters and transverse ribs In some gravel-bed channels, clusters of bed particles can form when small particles group around one or more large particles (Brayshaw *et al*., 1983). Clusters impede particle entrainment because all particles in the cluster do not move until the key particles do. They are perhaps most readily formed where the range in particle size is wide (Fujiko Iseya, personal communication).

Transverse ribs -- lines of large clasts across the channel that are usually one or two diameters wide (Koster, 1978) -- and step-pools -- natural boulder weirs separated by plunge pools (Whittaker & Jaeggi, 1982)--are common small-scale bed forms in steep channels (slopes from 1 to 10%). Unlike clusters, transverse ribs and steps commonly span most or all of the channel. Steps are believed to form during low rates of transport of large clasts or during final stages of a debris flow or torrent (Sawada *et al*., 1983). Like sheets, transverse ribs and steps may form where large particles moving over smaller bed material encounter increased grain roughness created by other large particles -- a mechanism that could manifest the kinematic wave theory of Langbein & Leopold (1968). Whether hydraulic jumps around step-pools are a primary or secondary process in their formation is a matter of disagreement. Whittaker (this volume) describes some effects of step-pools on bedload transport.

Bars and pools Bar-pool or scour-lobe units are key elements governing behavior of meandering and braided channels (Ashmore, 1982; Fujita & Muramoto, 1985; Thompson, 1986). These units exist at various scales up to channel-widths long, and consist of sequences of flow convergence that scours a pool and flow divergence downstream that deposits a bar or lobe. Measured frictional losses from bars during bedload-transporting stages vary from 0 to 75% from river to river (Parker & Peterson, 1980; Prestegaard, 1983; Ikeda, 1984). Frictional losses from bars decrease as stage increases (Parker & Peterson, 1980) and as supplies of readily transported bedload increase (Lisle, 1982). Predicting the dimensions and resulting friction of bars remains an important missing link in predicting the behavior and sediment yield of gravel channels.

Alternate bars form in gravel channels conceivably to transport bedload where, on average, entrainment thresholds are exceeded by a small factor. Parker (1978) determined theoretically that bankfull discharge in gravel channels exceeds critical discharge of entrainment by a factor of only 1.2. Under such conditions, the channel can most efficiently transport sediment by creating zones of concentrated stream power (Fujiko Iseya, personal communication). Such is achieved in alternate bars, where bedload converges into zones of increasing unit stream power (pools) and diverges over zones of decreasing unit stream power (bars). Bedload can thereby be transported at substantial rates in quasi-equilibrium with channel morphology.

Research into the mechanics of bar-pool units is a promising avenue for advancement of general understanding of channel behavior. Such research has been carried out in greatest detail and attention to physics in meanders (Dietrich & Smith, 1984).

Influence of non-alluvial bends and obstructions

Scour and deposition around bedrock bends and large obstructions in or along channels can cause bars to form where they would not form otherwise (Kinoshita & Miwa, 1974; Florsheim, 1985) or at least fix the positions of bars and pools (O'Connor *et al*., 1986; Lisle, 1986). Stabilization of bar-pool topography may thereby govern channel courses over long periods and affect the construction of floodplains (Lisle, 1986).

Large woody debris is a highly dynamic and supply-dependent form of natural channel. structure that has received much attention by researchers and managers responsible for maintaining fish habitat in managed forest streams (Swanson, *et al*., 1976; among others). Individual pieces or accumulations of large woody debris that are at least one channel-width long commonly form the most favorable habitats, such as pools, for fish and other aquatic organisms (Keller & Tally, 1979; Bisson & Sedell, 1984). Hogan (this volume) describes how reducing the size of woody debris by timber harvesting can grossly destabilize forest stream channels.

As a result of the strong influence of irregular, non-alluvial boundaries and a weakness in the tendency to form bars in some mountain streams, regularly repeating bar-pool sequences may not be present or easily delineated. Grant (1986) and Sullivan (1986) define channel unit types, e.g., pools, rapids, and cascades, that are not necessarily tied to freely formed bar-pool sequences, but have quantifiable, hydraulic and morphologic domains.

Bedrock bends and large obstructions are common in many steepland channels, especially in unglaciated, moderately narrow valleys. What is not known is how frequent are these features and how important is their influence on the behavior of channels of different patterns and on floodplain development in valleys of different widths. And under what conditions do bar-pool sequences form only in association with non-alluvial bends and obstructions, become fixed in positions dictated by these features, or migrate through a series of these features?

Braided channels

At present, few accurate, quantitative predictions of the form and behavior of braided channels can be made. Measurement of bedload transport rates and characterization of the form and hydraulics of braided channels are confounded by the instability of anabranches and the wide range of flows capable of altering them (Mosley, 1982; Davies, in press).

To sort out the complexities of braided channels, it can be enlightening to focus on scour-lobe units which form nodes governing local channel behavior (Ashmore, 1982). The equilibrium achieved in convergence and divergence of bedload in alternate bar sequences breaks down in braided channels, because divergence of bedload transported onto a bar apparently does not compensate for decreasing stream power. Bedload deposits laterally and vertically and causes the bar to grow until one or more new channels are incised around it (Davoran & Mosley, 1986). This mechanism is compatible with Carson's (1984) argument that the greatest tendency for braiding is in unconfined gravel channels that have large supplies of mobile bedload.

Disequilibrium in scour-lobe units can lead to great complexity in channel behavior. Scour-lobe units in disequilibrium may migrate upstream or downstream depending on changing balances between scour intensity and local bedload supply. They can cause small-scale adjustments between minor anabranches at low flow (Mosley, 1982) or they can govern bar migration and bank erosion over a number of years (Ferguson & Werrity, 1983). Thompson (in press) reasons that scour-lobe formation can lead to either channel narrowing and degradation or widening and aggradation, depending on width-depth ratio. Ashmore (this volume) shows how these mechanisms proceed as sediment waves pass through braided channels.

BEHAVIOR OF STEEPLAND CHANNELS

Steepland channels of any order commonly have narrow and discontinuous floodplains. In this respect, and because of their steep slopes, steepland rivers resemble headwater tributaries of lowlands. This analogy highlights several important differences in behavior between steepland and lowland rivers. Direct inputs of sediment from hillslopes to steepland rivers cause sediment transport to be episodic. Resistant non-alluvial boundaries inhibit lateral migration and can control the position of macro-bedforms. Discharge is highly variable and sediment rating curves tend to be steep. As a result of these characteristics shared with headwater channels (Wolman & Miller, 1960), dominant channel-forming discharges tend to be less frequent in steepland rivers than in lowland rivers.

High-magnitude, infrequent floods can be especially effective in shaping steepland channels. Steep hillslopes and channels and locally constricted valley bottoms can generate extreme unit stream power. Bed or bank materials may be too large or resistant to erode at all but extreme events (Baker, 1977; Pickup & Warner, 1976; O'Connor _et al_., 1986); thus post-flood flows that carry only modest amounts of sediment may be unable to reverse effects of large floods. Also debris flows which often occur in conjunction with large floods may deliver material whose large particle size and topographic position on the valley floor render it immobile to later flows. Using the classic approach of Wolman & Miller (1960) Nolan _et al_. (this volume) demonstrate that large infrequent floods in rivers of northwestern California transport a disproportionate amount of suspended sediment and that bankfull discharge occurs less frequently than in other areas.

SEDIMENT ROUTING AND BASIN-LEVEL CHANNEL MORPHOLOGY

The study of sediment routing is important to understanding channel behavior because it forces us to explore linkages between sediment transport and channel morphology at a drainage-basin scale. At this scale, it is impractical to trace the transport of sediment particles over a long period, and short-term observations will document the operation of the system in only one of many possible permutations. Probability and continuity models may offer the best theoretical approach.

Sediment transport — channel morphology models

The downstream transfer of sediment in steepland channels commonly shows discontinuities due to concentrated inputs and pronounced tendencies for transport or storage of sediment in particular reaches (Church, 1983; Kelsey, this volume). Modeling the transport of large sediment inputs down channel systems using equations for sediment transport and continuity can be useful (Pickup *et al*., 1983). Such models are hampered, however, by unreliable sediment discharge functions and linkages with the geometry, friction, and armoring of erodible channels (Dawdy & Vanoni, 1986). Another problem is that sediment transport regimes may appear to be either supply-dependent -- responsive to volumes of new sediment supplies entering the channel -- or stream-power dependent -- responsive to the magnitude of flow and shear stress in the channel. Since most channels are formed in sediment, however, the origins of these transport regimes are unclear. Presumably, channel morphology and the distribution of sediment size adjust in poorly understood ways to the recent history of sediment inputs. Orsborn & Stypula (this volume) present a model for predicting channel geometry in Oregon based in part on a new expression relating channel boundary shear to channel shape.

Reservoir theory

As an alternative to models containing equations for flow, channel geometry and sediment transport, reservoir theory emphasizes transfer and storage of sediment through a series of reservoirs (Eriksson, 1971; Dietrich *et al*., 1982). Channel systems contain various types of reservoirs, including the active channel bed, bars, floodplains, and terraces, that are characterized by different levels of activity. The transit time and fate of particles entering a channel system are sensitive to interchanges with reservoirs having different turnover times (Madej, this volume). Although such linkages are difficult to quantify, Kelsey *et al*. (1986) found that a mathematical model for sediment routing based on a first-order Markov chain was most consistent with data from Redwood Creek in northern California when minimum interchange between reservoirs was assumed. This suggests simple applications of reservoir theory may be valid in some cases, but the frequency of sediment interchange between reservoirs needs to be investigated elsewhere.

In order to develop a sediment budget based on reservoir theory, the volumes of storage reservoirs and the age distribution of sediment stored in each must be measured. Dating sediment -- a difficult though necessary task in formulating such a model -- can be done by interpreting the record of sediment movement preserved in vegetation. Applying vegetative dating techniques to the reservoir modeling proposed by Dietrich et al. (1982), Nakamura et al. (this volume) show some important differences between upstream and downstream reaches in the transport and storage of sediment in five rivers in Japan.

Reservoir theory can be used with limited information on reservoir interactions to estimate quantitatively the sediment routing through a drainage system only if a steady state can be assumed. This condition poses a problem in steepland drainages where there can be large perturbations in sediment routing and .if predictions on the behavior of a non-steady state such as the effects of a volcanic eruption or land-use disturbance are desired. Reservoir theory can reveal, however, where changes in drainage-basin sediment transport systems can be expected to take place. On the other hand, increased understanding of the response of channels to changes in sediment transport from a physical standpoint may improve our ability to apply reservoir theory in unstable systems.

CONCLUSIONS

Field conditions for directly studying sediment transport in steepland channels are formidable, and their behavior is complex and episodic. Therefore, many of the important advances are being made through laboratory experiments and the development of mathematical models based on physics and probability. The most rapid advances are being made in bedload transport in heterogeneous gravel beds, sediment transport at high concentrations, and sediment routing. Less progress has been made in attacking the long-standing problem of the inter-relations of sediment transport, friction and channel morphology, perhaps because of the greater complexities of behavior, at this intermediate scale. The widespread control of steepland channels by non-alluvial boundaries has received little attention and adds further complexity by invalidating the assumption of self-formation of channels. Such complexities can be ignored in applications of reservoir theory by disregarding sediment transport and river mechanics and instead by determining mass balances using the age and volume of sediment stored in reservoirs.

As we gain greater understanding of channel behavior at several intervals of scale in space and time, we are perhaps reaching a point where there are more and more opportunities to use new knowledge at one scale to advance that at another.

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