# REVIEWS OF THEME 2

## Stream Channel Dynamics and Morphology

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The nine papers presented provide an important overview to the subject areas of sediment transport, channel dynamics, and channel morphology. After reviewing these papers, one might be torn between two divergent viewpoints. The first is that the professions of geomorphology, hydrology, and related fields have made considerable progress during the last five years in understanding the interaction of sediment movement and the role of channel morphology. Certainly if this symposium had been convened five years ago, our "state of knowledge" would have been relatively limited. Over the last five to ten years, the number of researchers and the amount of research information being published has increased greatly. Although this situation may seem satisfying to those leading research or teaching efforts in this general subject area, the second and opposing viewpoint is that we have barely scratched the surface in our understanding of channel processes and characteristics. This opposing viewpoint becomes particularly apparent when we attempt to extrapolate information from one watershed to the next. We are seldom successful at doing so. Although the processes are complex and simple solutions should not necessarily be expected, the need to identify and understand the basic physics of stream systems is prerequisite to solving the difficult problems faced by researchers and land managers.

On a conceptual basis, the sedimentation process has several major components: (1) the detachment or entrainment of particles, (2) the transport or movement of the particles, and (3) deposition. This conceptual framework also indicates that there are several ways of assessing factors affecting channel dynamics. One can approach the problem by evaluating scour (degradation) and fill ((aggradation) within the stream system. However, these state variables provide limited insight into the dynamics of sediment transport. Alternatively, the transport processes definitely illustrate the temporal and spatial variability of stream dynamics but they have not been useful for predicting changes in channel morphology. Future studies need to evaluate both state and process variables concurrently before these linkages can be firmly established. Although researchers working with selected channel reaches may concentrate on what is happening within that reach, they need to be continually aware of other hillslope or channel processes further "upstream" which may directly affect their results.

Perhaps one of the promising methodologies for studying erosional and transport processes is through the use of sediment budgets. This type of accounting process identifies sediment movement over selected time intervals. A major advantage of utilizing a sediment budget is that it forces a researcher to consider all of the major sources or processes affecting sediment movement and to identify the relative importance of each. It provides a systematic perspective from which more detailed process studies may be developed. The sediment budget approach is perhaps a carryover from radiation transfer theory and associated energy budgets. Unfortunately, sources (sediment suppliers) and sinks (locales of sediment deposition) are often not easy to define. What may be a sink for one set of processes may later become a source under different conditions. The factors affecting transfers of sediment within a system are highly variable and interactive making the delineation of cause-and-effect often impossible. There is also the problem that the amount of sediment transferred by a given set of processes may not be easily measurable and thus is calculated as the residual term in the sediment budget. Unfortunately, the culmination of all measurement errors will tend to be concentrated in those processes which we know the least about. Continuing the analogy with energy budgets, where the quality of radiation can shift (e.g., shortwave to longwave), the characteristics of the mobilized sediments can change from larger to smaller particles depending upon initial particle hardness, transport distances, weathering processes, etc. Finally, caution must be exercised in making judgments concerning the representativeness of sediment budget data collected even over several years. Many erosional and sediment transport processes operate over widely varied space and time scales. The time period sampled during any sediment budget study may thus have an overwhelming effect on the results and conclusions.

Due to the variety of research objectives and problems being addressed by those presenting papers on stream channel dynamics and morphology, a multitude of methods were presented. These included watershed studies, plot studies, field calibration of theoretical and empirical equations, flume studies, etc. Also, a variety of data gathering techniques were employed (e.g., tracers, videotapes, bedload samplers, cross-section profiles). In some cases the methods and techniques have become fairly standardized, but in most cases researchers have adapted and modified various techniques to meet specific requirements. Although a plea for more uniformity in the presentation of data is valid, I suspect considerable opportunity exists for developing new measurement methods and techniques. Future research may indeed require more sophistication and innovation to tackle complex problems. In addition, now that background information is beginning to accumulate on various in-channel processes, there is an increased need for experimentation. Historically, flumes have been used for this purpose but full-scale channel experiments are needed to better understanding channel processes and for developing predictive relationships.

Several of the presented papers utilized standard statistical techniques in their data analysis. Although these techniques have been extremely useful in identifying the relative importance of various factors affecting sediment transport processes, the inherent limitations of many statistical analyses reduce their effectiveness when applied to time series data. Material in transport (suspended solids, bedload, organic matter) and various hydraulic variables (stage, velocity, discharge, shear stress) all exhibit a tendency toward autocorrelation whereby a measured value at time t+1 is dependent upon what was measured at time t. As a result, regressions seldom have independently distributed variables. This problem becomes more pronounced as measurement frequency increases. Thus, standard hypothesis testing and tests of significance are of limited utility. In addition, such relationships can seldom be extrapolated with confidence. Improved analytical techniques for time series data are needed. Furthermore, the substitution of space for time opens additional possibilities for evaluating channel morphology characteristics using time series analytical techniques.

The transport of bedload was discussed by a number of papers in this session and is a major factor affecting the morphology of channels. Although there are numerous uncertainties about how, when, and under what hydraulic conditions bedload sediment moves, there seems to be a concensus that these sediments move downstream as a wave form, a slug of material or a zone of relatively high particle concentration. There are several conditions in natural channels which undoubtedly play a significant role in bedload transport and which need to be better understood before we can fully appreciate the mechanisms by which bedload movement occurs. These include:

1. Nonuniform channel geometry: As a result of pools/riffles, pools/falls or any irregular channel geometry, the general pattern of flow through the stream system indicates this water is continually accelerating and decelerating. Changes in channel morphology in a downstream direction can thereby have a pronounced effect on the local average velocities, velocity profiles, bottom shear stresses, and other hydraulic parameters. Turbulence characteristics would similarly be affected. Furthermore, this condition of irregular channel geometry may lead to situations where stream velocities along the bottom of pools may exceed those over riffles at high flows (e.g., the concept of "velocity reversal"). The result of these varying hydraulic conditions is that discrete sections of a channel may be undergoing scour while other sections are dominated by transport or deposition processes. Furthermore, the exact role of each channel section changes as flows are increased or decreased.
2. Transient flows: During a typical storm, flow rates are often rapidly increasing or decreasing over time. Thus, bedload transport is continually responding to these changing flows and any resultant change in the availability of bedload sediments. Apparently, a stream seldom attains a condition of steady state in regards to bedload transport rates. Although the increase and decrease in flows during a period of storm runoff is often a smooth continuous function, the thresholds at which individual sections of a channel become active in the bedload transport process will vary greatly. This situation may at least partially account for the high temporal variability of bedload transport measurements.
3. Nonuniform particle size: At any given location in an alluvial channel, the particle sizes of materials comprising the streambed will

vary over one, or perhaps two, orders of magnitude. Additional variability in particle size is encountered spatially at various locations along a given riffle or between the bed sediments of pools and riffles. Furthermore, the armouring of riffle sediments provides a mechanism by which the underlying smaller particles are unavailable for transport until the armour layer is disrupted at high flows.

All of the above factors indicate that the transport rates of bedload sediments should be highly variable in time and space. Indeed, this situation was well illustrated in several of the presented papers. Attempts to extrapolate steady-state transport equations, developed from conditions of uniform flow, uniform particle sizes and uniform channel geometry, to predict bedload movement in mountain streams seem destined to failure. Perhaps the problem of variability in natural channels is so great that we will never be able to accurately and deterministically predict bedload transport. Certainly, we need to take a closer look at the above factors and their role in scour, transport, and deposition processes.

Unfortunately, there are few universal answers to the complex problems related to stream dynamics and morphology. After we are past the assumption that both water and sediment move downhill, the system very quickly becomes complex. I see no lack of challenges to future researchers in geomorphology, hydrology, and related fields of interest. Indeed, many research efforts are spread very thin. Thus, we need to maximise future research effectiveness by being better informed and more efficient scientists. I trust this symposium has assisted in accomplishing these goals.

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The papers presented under Theme 2 showed clearly that very little is known about sediment transport processes in steep channels. Each paper reached conclusions which were either very general or qualified so as to make obvious the need for further work in the area.

Appropriately the first paper presented a means of delineating different flow types based on the relationship between Froude number and slope angle. That material of this nature is being presented surely indicates that the subject is still in its infancy. Examples from a highly eroding basin in Japan were used to illustrate the various flow types and were, I felt, useful in that they alerted everybody to the very wide range of flow phenomena to be discussed during the session.

Two of the possible flow types were treated by subsequent papers. Debris, mud or grain flows (the terminology is not agreed upon) were treated in two papers while the remaining papers dealt essentially with sediment movement as bed load.

Mizuyama's paper (p 212–224 of the Proceedings volume) was based on results from controlled laboratory studies of debris flows. Figures 3 and 4 show great variability in results from what seem to be identical experiments. No doubt variations under field conditions are much larger. Other factors not observed or recorded must have influenced these results. It is clear that more basic research into mechanisms must be undertaken. Ward and O'Brien (p 269–286) have made a start in this direction by predicting velocity profiles with some success. However this is not a good test of the correctness of the mechanism postulated as a basis for the calculation. In clear-water boundary-layer flows, provided a reasonable assumption is made (e.g. mixing length hypothesis, similarity hypothesis), good agreement between predicted and measured velocity profiles is always obtained. The case is probably similar with debris flows. More stringent tests for mechanisms need to be found. One such would be particle concentration and size distribution within the flow.

Further understanding of debris flows will come only with improved experimental work. Systematic observation and fully compiled records will be essential in this effort. The suggestions given by Ward and O'Brien for such recording are excellent and should be heeded by workers in both the field and the laboratory.

The one aspect of bedload transport that stood out during the session was the seemingly independent behaviour of the water and sediment flows. Figures 4, 5 and 6 from Ashida, Takahashi and Sawada's paper show this very clearly. Similar data is provided by Beschta from an Oregon basin (p 188). The evidence is strongly indicative of events in the channel controlling sediment discharge more firmly than does the water discharge. Possibilities are bank slumping, breakup of armour layers and the effect of pools and riffles acting as storage units. No formula is going to predict sediment transport rates at a site as functions of flow at that site under these conditions. Attempts to do this should be terminated.

There is hope that sediment yields associated with sequences of flows may be predicted to within limits acceptable to engineers and planners. Data of the type presented by Meade, Emmett and Myrick (p 225–235) would be most useful in developing any such relationship. The concept of gravel waves which is supported by the data given by these authors, has been gaining acceptance, with reports on gravel wave movement appearing more frequently. This is an important channel process which negates the traditional laboratory approach to sediment-transport rate determination. More realistic laboratory experiments involving pools and riffles need to be devised so that a basic understanding of the movement of these waves can be obtained.

It is not known whether pools and riffles are necessary for the formation of gravel waves. Could a buildup process, similar to that by which sand bedforms develop occur in steep channels without pools? A chance piling-up may inhibit the motion of other particles which add to the original obstruction and cause further interference. One effect of medium-sized floods may be to establish gravel waves from sediment deposited into the channel over considerable lengths.

Careful laboratory and field observations are needed to establish the ways in which gravel waves form. Lisle's work (p 189–211) with the recovery of aggraded stream channels could well be extended into this area. Do gravel waves form as aggraded channels recover? If so what are the mechanisms, time scales and geometric parameters? I see a blend of Lisle's work with the careful profiling and sampling done by Meade *et al.* being a fruitful area for future work.

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Studies of physical systems such as stream channels can be subdivided into field data empiricism, in-laboratory physical model empiricism, theoretical analysis of the underlying, controlling physical processes, and mathematical modelling of stream channel systems. The last group of studies is relatively recent, owing to the emergence of high speed, electronic computers, and has its roots in the first three types. No matter which type of study is undertaken, there are basic underlying principles that must be recalled and applied to the situation at hand. For sediment transport in channels (steep or otherwise) of steeplands, a basic principle is that you can't transport more material than is available. In other words, is the transport process we measure being controlled by the capacity of the flow or by the supply of sediment?

Discharge is one key variable in a maze of interacting variables that control stream channel dynamics and morphology through sediment transport, erosion, and deposition. It doesn't particularly matter how the water gets into the channel, just that the discharge has attained a certain level (except as noted below). What does concern us is what it carries into the channel — sediment, debris, cars, etc., and what work it might do in shaping or reshaping the channel geometry. The dynamic interaction of discharge is best, or most often, related to the applied shear stress, represented as a function of depth and slope or as a function of velocity. In either case, a knowledge of the stream channel geometry is needed. However, the stream geometry changes as the flow moves the loose or erodible materials into new configurations, which in turn alters the effect of the discharge, and so on. Not only does the discharge alter the channel boundary, the channel boundary alters the depth and velocity of the discharge through flow resistance and energy losses via bottom roughness, gravel bars, or organic debris. Of interest, also, is the longitudinal profile of the channel in terms of the bed slope and how it is modified. Ashida et al's paper on the effects of bed slope on shear stress and the formations of turbulent fall-plunge pool-fall "stair steps" in a channel are important concepts that must be considered in delineating a steep channel system. It is apparent that the transport capacity of the discharge is not only dependent on the magnitude of the discharge but on how discharge is modified by channel characteristics to produce the shear stresses and turbulence necessary for transport.

On the other side of the coin are the supply controls. Sediment supply to a channel or reach of channel can come from several sources. Upland and tributary sources from landslides, gullies, sheet wash, and channels were touched upon by Grant, Meade *et al.* and Loughran *et al.* in their papers. The volume of material being supplied from upstream and tributary sources depends upon watershed and channel factors not related to the stream reach under consideration. Slaughter and Collins discuss this in relation to permafrost watersheds in Alaska, and Loughran *et al.* examined a forested and grassland basin in Australia. Grant puts a historical perspective on supply of sediment with his work in New Zealand. The channel itself also serves as a sediment supply. Channel banks are subject to mass wasting, and as water levels rise, more area is exposed to erosion. Beschta's observations in an Oregon Coast Range watershed reaffirm the interaction of stream stage and bank supply of materials. Lisle's discussion of the large amounts of landslide debris from steep, high stream-banks and its effects on rivers in northern California is a reminder of this often overlooked source of sediment. Channel bottoms are another potential source of material; often the underlying, more erodible materials are protected by an armour layer of coarser sediment. Unfortunately, Day was not able to attend and present his paper on his experimental study of bed armouring in steep, coarse-bed channels. There were many questions and comments that his study addressed which were not discussed. Storage of materials in channel bottoms and banks after transport decreases from a drop in discharge is a related aspect as presented by Meade *et al.*, Lisle, and Loughran *et al.* The concept of "effective" discharge is relevant in this regard as it not only represents the discharge at which the channel is eroded, but also the level at which deposition of the armour layer begins and the new shape of the channel (storage, pools, riffles) is established. Sediment type and size is of particular importance as it affects the relative forces needed for transport of materials and modifies the flow characteristics of the discharge.

Most channels of steepland areas are supply limited because of upstream sources or bed and bank armouring. Although the transport capacity exists, it exists for sediment sizes that are not available. This is evident to those who have attempted to apply sediment transport equations developed for "infinite" supply situations or theoretical relationships. Such equations will tend to overpredict for cases where there is a lack of sediment supply. In cases of underprediction, flow conditions other than those the equations were developed for are often responsible.

Evident in a majority of the papers in this theme were the changes in storage and supply mechanisms that controlled transport rate and yield. Beschta's paper shows what happens when the annual production of sediment upstream of the sampling point is flushed out or restored in another part of the watershed-channel system. Lisle reiterates this point; supply mechanisms can drastically change the storage locations of materials in a watershed. Meade *et al.*, Lisle, and Loughran *et al.* all refer to in-channel storage supply mechanisms.

Most of the above papers are focused on channels with slopes less than 5%. However, the papers by Ashida *et al.*, Mizuyama, and Ward and O'Brien contrast these with processes in steep channels greater than 5%. Ikeya, in presenting Mizuyama's paper, demonstrated the tremendous forces that occur in steep channels. These forces are rare, if existent at all, in most other channels. His films will long be remembered. In Ashida *et al.*, slope was used to subdivide transport processes. The presentation added to this, as plunge-pool dynamics of steep "stair-stepped" channels were discussed. Ward and O'Brien showed the difficulties in physically and mathematically modelling the unsteady, non-uniform flow of debris flows. Although flow in steep channels is turbulent and can produce a wide array of transport phenomena, there are similarities that exist between the types. Of particular note is the observation that the ratio of volumetric sediment discharge to volumetric water discharge is a function of slope for bed-load transport and has an upper limit of about 1.0 for debris flows. The finding that the ratio is a constant at a particular slope is reasonable if tractive force criteria are considered. However, it appears as though the grain size plays an important role. Again, such relationships hold only for transport-capacity controlled situations, i.e., infinite supply.

Each of these papers presents a minute look at one or more channel processes either from field studies, laboratory studies, or theoretical considerations. Together they show the complexity of the channel system. Three general areas need more studies. These are:

1. The supply side of the equation. Specifically,
    a What moves, what are the sources?
    b When does it move?
    c How much moves before it is halted by other processes?
2. Along the same lines, consideration should be made of
    a Longitudinal and lateral erosion, deposition and storage
    b Armouring of the channel bottom
    c Transport over armoured beds
    d Effects of local and general scour

and

3. What are the controlling processes in steep channels — the forces, geometry and sediment transport types?

Understanding of these areas will add to our knowledge of and our ability to predict stream channel dynamics and morphology.