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A descriptive model of bed material routing was developed for alluvial streams exhibiting sequences of pools and armored riffles. The model assumes that channel geometry, sediment transport competence and the availability of sediments for transport are all non-uniform in the downstream direction. Bedload transport is described as occurring in two relatively distinct phases. Phase I involves the transport of predominantly sand-sized bed materials over stable riffles. Phase II occurs at flows which are greater than those required to entrain riffle armor and involves the transport of riffle sediments in addition to Phase I sediments.

Phase I bedload transport was sampled during three high flow events at Flynn Creek, a 2 km^2, third order drainage in the Oregon Coast Range and at Huntington Creek in the Wasatch Plateau of central Utah during a controlled release of water from Electric Lake reservoir. A power relationship existed between Phase I bedload

transport and discharge at Flynn Creek. The relationship was consistent between storms and between years. At Huntington Creek, Phase I bedload transport correlated with discharge on the rising limb of the hydrograph, but transport rates decreased over time at constant discharge, indicating a sediment supply control over Phase I transport.

Phase II bedload transport was sampled at Flynn Creek during a 1.8 year return period streamflow event in February, 1979. Bedload transport rates were closely correlated with the storage and release of bed material from the riffle at the bedload sampling cross section; transport peaks corresponded to periods of scour and large decreases in transport occurred during periods of deposition. Particle size analysis of the bed material in transport showed as much as a 12-fold increase in the transport of large (> 12.5 mm diameter) bed material during periods of riffle scour. Phase II transport, which involves rapid scour and redeposition of riffles, can be described as highly non-uniform in a downstream direction and highly unsteady at any point over time. At Flynn Creek, significant scour and redeposition of riffles can be expected to occur on an average of once every one to two years.

Corresponding to the two phases of bedload transport are two processes which result in changes in the particle size composition of riffle sediments. First, the intrusion of fine sediments into the pore spaces of stable riffles dominates during Phase I transport. Second, the deposition of entirely new riffle features occurs during Phase II transport. Deposition is often associated with one or more streambed scour and fill sequences and is the direct result of instantaneous differences in sediment transport rates between different channel locations.

The particle size gradation of riffles is determined primarily by bed material deposition. Sampling at Flynn Creek indicated that a riffle contains the range of sediment sizes found in transport at the time of deposition but, over all, is more coarse than the particle size distribution of sediment in transport. In flume studies of the deposition process, riffle composition was shown to be sensitive to the rate of sediment transport at the time of deposition--becoming more coarse at lower transport rates. Small but significant ($p = 0.95$) decreases in the median particle diameter of riffle sediments resulted as the sediment mixture in transport increased from a 1:1 to a 5:1 sand-to-gravel ratio.

Flume studies showed the intrusion process to be selective towards finer sediments which cannot be filtered by the riffle sediment matrix. Intrusion may decrease or even cease if filterable sediments block surface pores in riffle substrate. Intrusion, if it occurs, is a function of two factors: (1) the pore size distribution of the stable riffle feature, and (2) the particle size distribution and concentration of suspended and Phase I bedload sediments in transport immediately above the streambed.

Bed Material Routing and Streambed
Composition in Alluvial Channels

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"A clear understanding that science is a radical simplification of our experience, that it considers only what is measurable and mathematically lawful in events, and that it therefore exercises a severe abstraction in its view of the world, is essential to any adequate philosophy of science."

—— John Compton, 1980

"The storm starts
when the drops start dropping,
When the drops stop dropping
the storm starts stopping."

—— Dr. Seuss, 1979

Bed Material Routing and Streambed
Composition in Alluvial Channels

I. INTRODUCTION

The Problem

The bed of an alluvial stream channel provides temporary storage for sediments in transport. During periods of high flow the exchange of sediment particles between active transport and the streambed is an integral part of the sediment routing process. At low flow, gravel bed features are relatively stable and serve as habitat for stream flora, benthic invertebrates and fish.

Previous studies (e.g., Andrews, 1979; Edwards, 1980; O'Leary, 1980) suggest that bedload transport rates in alluvial channels may not always be direct functions of stream discharge. In addition, these studies indicate that bedload transport events are often accompanied by seemingly random occurrences of streambed aggredation and degredation at selected channel cross sections. This suggests that in addition to stream energy considerations, sediment continuity and sediment availability considerations may be important in describing bed material routing in small alluvial channels. Changes in sediment storage on the streambed may influence both instantaneous sediment transport rates and the particle size composition of alluvial channel substrates.

The purposes of this study are to (1) develop a descriptive model of bed material transport in alluvial channels exhibiting sequences of pools and armored riffles, (2) demonstrate aspects of the model in natural streams, and (3) identify important streamflow and sediment variables which affect changes in the particle size composition of streambed gravels.

Hypothesis

Four fundamental concepts form the basis for hypothesizing a descriptive model of bed material transport in alluvial channels exhibiting sequences of pools and armored riffles:

1. Channel cross section geometries are non-uniform in the downstream direction. Particularly pronounced differences in cross section geometry commonly occur between riffles and pools.

2. Flow conditions are non-uniform in the downstream direction for any given discharge. This results directly in relative differences in the sediment transport competence of the flow at different locations in the channel. Again, these differences may be most pronounced between riffle and pool sections. Not only are transport competences different between riffle and pool sections, but the relative difference varies as a function of stream discharge. Keller (1971) and Lisle (1979) have demonstrated that at flows considerably less than bankfull, sediment transport competence is greater over riffles than in pools. However, as flows increase, the rate of increase in sediment transport competence is greater in pools than over riffles, until at flows approaching bankfull the stream is more competent to transport sediments through pools than over riffles.

3. The availability of sediments for transport is non-uniform in the downstream direction. In this study, two relatively distinct sources of bed sediments are defined. Phase I sediments are bed surface deposits of sand and fine gravel located primarily in pools, along channel edges and behind obstructions. They are easily entrained and transported upon rising streamflows. Phase II sediments are the coarser sediments, including the armor gravels, which comprise riffles. They are relatively less easily entrained than Phase I sediments and higher flows are required for their transport.

4. Sediment continuity considerations imply that if an alluvial stream channel undergoes local changes in sediment storage, as indicated by streambed aggradation or degradation, then instantaneous bedload transport rates are non-uniform in the downstream direction and unsteady over time at any single channel location. The concept of non-uniform sediment transport competence suggests that such local changes in sediment storage may be necessary aspects of the process of bed material routing.

The above four concepts provide the basis for hypothesizing a two-phase model of bedload transport in alluvial channels exhibiting sequences of pools and armored riffles. Phase I bedload transport is defined as the transport of Phase I sediments over stable riffles. Streamflows during Phase I transport are less than those required to entrain riffle armor sediments. Phase II bedload transport is defined as occurring at flows which are greater than those required to entrain the riffle armor. The bed material which comprises the riffles then becomes an important additional source of material for bedload transport, and the riffle becomes susceptible to scour and reformation.

Corresponding to the hypothesized system of bedload transport are two processes that have the capacity to affect changes in the particle size composition of stream gravel substrate. The first process occurs during Phase I transport when suspended sediments and Phase I bed sediments are transported over stable gravel beds and individual sediment particles intrude into the pore spaces of the stable substrate. The second process involves the deposition of entirely new gravel bed features. In the case of riffles, this process would occur during Phase II transport and may be associated with one or more riffle scour-fill sequences. It is suggested that the composition of the newly emplaced gravel bed is, in part, a function of the composition of bed material in transport and the rate of bedload transport during the period of bed material deposition.

Approach

The general approach to this study is to:

1. Identify the timing of streambed scour and fill in relation to a storm hydrograph and investigate interactions with bedload transport rates.
2. Identify sediment transport conditions at the time of bed material deposition and determine the sediment composition of the

resultant depositional features.

3. Identify sediment transport variables which affect the rate and extent of intrusion of fine bedload sediments into stable streambed gravels.
4. Examine the effects of the size gradation of transported sediments and the rate of transport on the composition of resultant depositional features.
5. Determine the effect of the transport of sand-sized sediments on the stability of coarser gravel bed features.

Figure 1 depicts the components of the study approach in relation to the study hypotheses.

The organization of the study is illustrated in Figure 2. Field studies were designed to demonstrate the two-phase model of bedload transport in natural streams. Flume studies were designed to gain additional insight into variables affecting the intrusion and deposition processes. The formulation of a descriptive model is the means by which all the study elements are brought together into an interrelated product.

Scale of Reference

The fluvial processes which influence bed morphology are characterized by numerous interdependent events which operate on a wide variety of temporal and spatial scales (Schumm, 1971). On the geologic time scale, geology, climate and biology interact to form gross

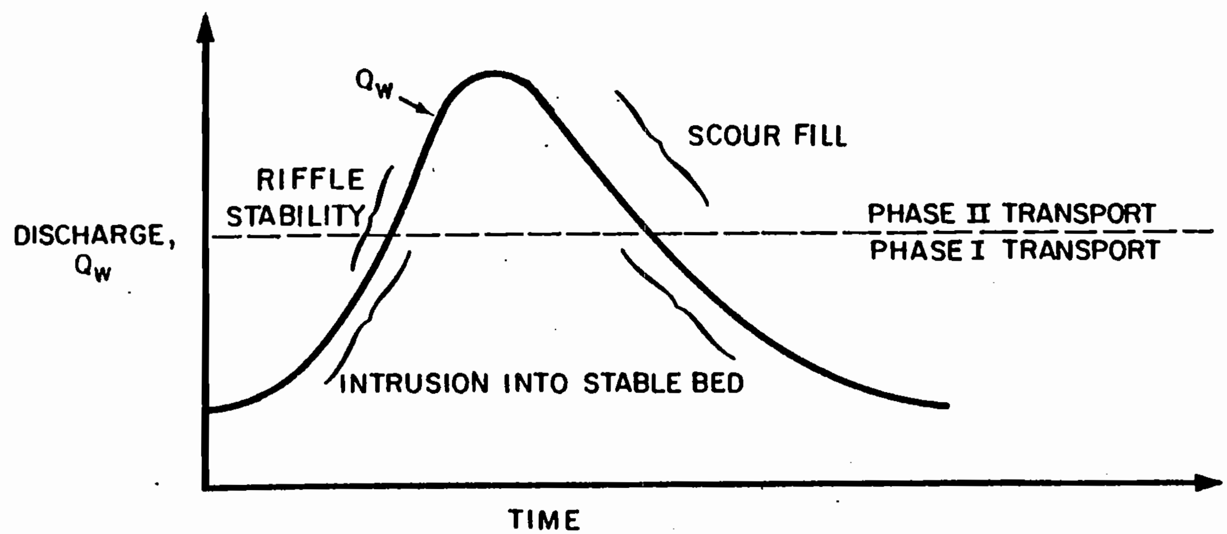


Figure 1. Schematic diagram of processes influencing the composition of riffle sediments in relation to study hypotheses.

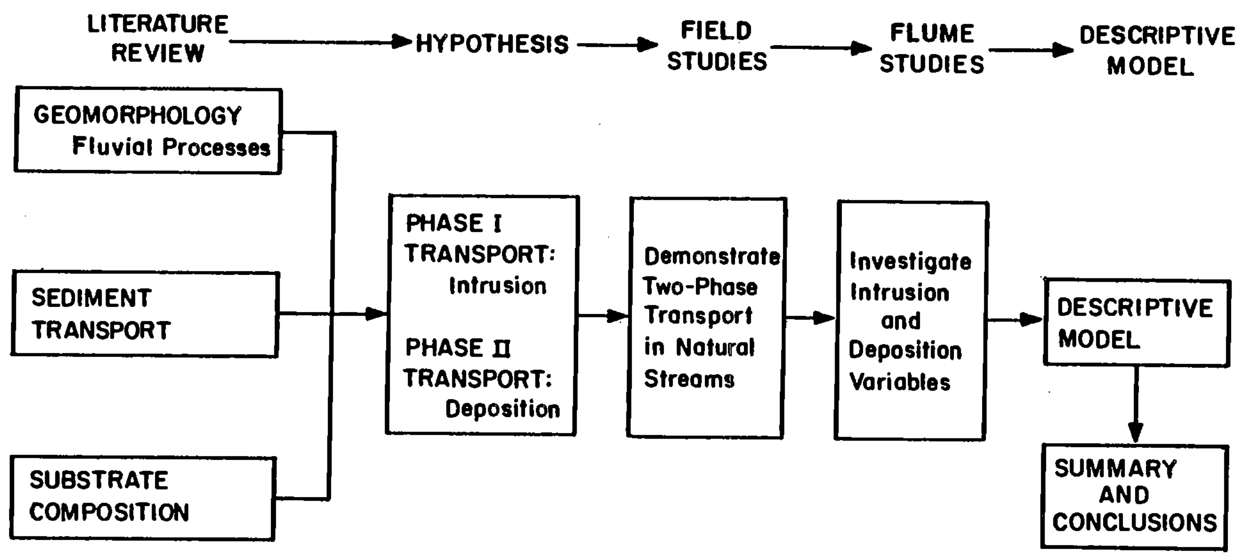


FIGURE 2. Organization of study.

morphologic and fluvial features. On a time scale of centuries, major episodic events such as large fires, landslides or catastrophic floods may trigger perturbations to the average sediment regime of a stream. On a time scale of years, annual erosion and sediment transport processes operate at "normal" rates as determined by hydrologic and watershed conditions. Most annual channel processes such as bedload sediment movement and adjustments in channel geometry occur relatively infrequently during brief periods of high streamflow (Dietrich and Dunne, 1978).

This study examined processes which occur on a seasonal basis during individual periods of high streamflow. The spatial scale is that of a short reach of stream--generally one or two pool-riffle sequences.

II. LITERATURE REVIEW

Physical processes affecting streambed form and composition have been studied by earth scientists, hydraulic and hydrologic engineers, and aquatic biologists. Large bodies of literature exist in the earth sciences concerning the development of river systems, river morphology, and erosion and sedimentation processes. The engineering sciences have addressed issues of channel stability and capacity, and the mechanics and prediction of sediment transport. The biologic sciences have studied sediment processes and streambed composition with regard to aquatic habitat.

While each of these disciplines approaches the subject of stream channel processes and conditions from a different perspective, each has made important contributions to the understanding of streambed processes and the factors affecting them. The literature review which follows summarizes selected contributions related to fluvial processes, sediment transport and streambed gravel conditions. The intent is to provide an overview of the physical processes which affect the routing of sediment in stream channels and control the composition of streambed gravels.

Fluvial Processes: Alluvial Channels

Morphology

Alluvial rivers flow in channels comprised of sediments previously transported by the river; they are free to adjust their dimensions, shape, pattern and gradient in response to hydraulic changes (Schumm, 1977). Alluvial channels are characterized by a changing horizontal position and by vertical instability in the form of bed scour and fill, and the downstream migration of bed features.

Channel morphology is influenced by the sediment and water moving through the stream system. Channel size is primarily the result of the dominant or bankfull discharge (Henderson, 1966), which is usually associated with a return period of 1.5 years (Dunne and Leopold, 1978). Schumm (1977) has suggested that ratios of annual peak to mean discharge may also be related to channel size. In addition, sediment load interacts with discharge to determine channel shape (Lacy, 1929; Schumm, 1960). Generally, alluvial channels with high width-to-depth ratios occur in relatively coarse noncohesive sediments whereas channels in fine cohesive sediments are narrower and deeper.

The slope of alluvial channels is often influenced by geologic controls or by the presence of large organic debris barriers. Rivers in fine alluvium, however, tend to be less steep than those in coarse alluvium (Schumm, 1977). The long profile of a channel in fluvial deposits tends to be intermediate between the theoretical least work profile and the profile of equal work per unit area (Leopold et al., 1964). An alluvial channel which has reached a balance among slope, channel characteristics, and discharge is said to be "graded" if its resulting hydraulic characteristics are the minimum required to transport the sediment load delivered to the channel (Leopold and Maddock, 1953).

Alluvial channels are often classified as bedload, mixed load, and suspended load channels or as straight, meandering or braided (Schumm, 1977). Bedload channels transport greater than 11% of their total load as bedload. Mixed load channels transport 3-11% of their total load as bedload and suspended load channels transport less than 3% of their total load as bedload. Bedload channels are typically straight, and mixed and suspended load channels typically are meandering. Braided channels generally are in loose, coarse alluvium and are relatively steep compared to meandering channels (Henderson, 1966).

The tendency of a river to meader has been demonstrated to be the result of the river working to minimize both total work and the longitudinal variation in work (Langbein and Leopold, 1964; Yang, 1971). The meander wave length is often related to discharge (Schumm, 1977).

Pool-Riffle Patterns

Pool-riffle sequences are commonly associated with alluvial channels in which at least part of the bed sediment is gravel sized or larger (Colby, 1964). Colby (1964, p. D25) defined a pool-riffle stream as "one in which the water surface alternates between long and comparatively level reaches (pools) and short and comparatively steep segments (riffles)." He further noted that while pool-riffle streams may have areas of sand bed, the riffles generally contain materials coarser than sand. In effect, riffles are gravel bars. Keller (1972) defined riffles as symmetrical shoals as opposed to point bars which are asymmetrical shoals.

Henderson (1966) and Leopold et al. (1964) believed that the pool-riffle phenomenon is closely related to meandering in its role as a mechanism for the dissipation of energy. Yang (1971) showed that riffles and pools in natural streams provide a means of self-adjustment of the channel that satisfies the law of least time rate of energy expenditure. In straight channels, pools and riffles have wavelengths similar to those of meanders. In meandering channels, riffles tend to form at the flow crossover between meander bends and the pools tend to form at meander bends (Fig. 3). However, Keller (1972) noted that pool-riffle spacing is independent of channel pattern. Yang (1971) noted that while the energy grade line is steeper over riffles than over pools at low flows, the difference diminishes as flows increase.

Richards (1976a) utilized autoregressive time series models to describe the geometry of riffle-pool sequences. Richards (1976b) found alluvial channels to be wider at riffles and narrower at pools at all stages of flow. Swanson and Lienkaemper (1978) suggested that in small, forested streams, organic debris may play an important role in controlling the location of channel features.

Keller (1971) observed that with increasing discharge the average bottom velocity of a pool increased faster than that of a riffle until a discharge approaching bankfull. At flows greater then bankfull the bottom velocity of the pool exceeded that of the riffle.

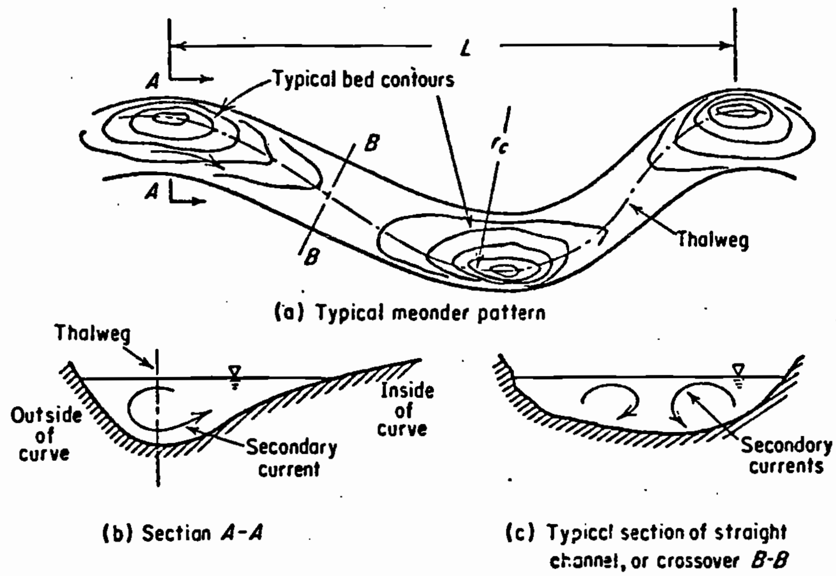


Figure 3. Flow Characteristics of Meandering and Straight Channels (from Henderson, 1966, p. 469).

This phenomenon of a velocity "reversal" is hypothesized to account for the maintenance of the riffle-pool sequences in alluvial channels. When discharge increases to a point where coarse riffle material is scoured, pool bottom velocities have already increased to a point which will not allow deposition in the pool. When flows decrease, it is hypothesized that the coarser riffle material is first deposited on the riffles. Upon further recession of flow, pool bottom velocities decrease below those of the riffle, at which point finer material transported over the riffle may be deposited in the pools. Lisle (1979) supported Keller's hypothesis by noting a corresponding reversal in transport competence as described by average bed shear stress over a riffle and pool on the East Fork River, Wyoming. Keller (1970), in painted stone experiments, demonstrated that the distance which a bed particle moves over a riffle is closely correlated to the bottom velocity at the riffle. In contrast, the distance which a bed particle moves in a pool is more closely correlated to the size and shape of the sediment particle.

Leopold et al. (1964) suggested that a gravel bar can be described as a kinematic wave with respect to the sediment particles moving through it. At the gravel bar the linear concentration of particles, as represented by mean particle density, is increased and individual particle speed is decreased. This theory suggests that individual particles move more continuously through pools than over riffles, where they may be temporarily stalled.

In general, the pool-riffle sequence appears to be the result of the least time rate-minimum variance laws of energy dissipation. The maintenance of the pool-riffle sequence and the associated aerial sorting of bed material is the result of the difference in hydraulic conditions between the pool and the riffle.

Channel Scour and Fill

Leopold and Maddock (1953) examined streambed scour and fill during the passage of individual floods at selected gauging stations on three rivers in the southwestern United States. They observed patterns of change in velocity, depth, suspended sediment transport and hydraulic roughness. Two patterns of scour and fill were noted. The first was characterized by an initial rise of the bed elevation during initial increases in discharge, followed by a decrease in bed elevation as discharge continued to increase, followed by a stable bed elevation during the recession of the flood. The second pattern was characterized by a general decrease in streambed elevation during increasing discharge followed by an increase in bed elevation during the recession of the flood.

In the first pattern of scour and fill, the point at which the bed stopped aggrading and began scouring corresponded to the flow above which breaks occurred in the linear relationships between the logarithms of discharge and the logarithms of velocity, suspended sediment discharge and depth. These observations indicated an intricate interaction between channel geometry, flow velocities, bed elevation and sediment discharge. Leopold and Maddock hypothesized that the depth of flow adjusted by means of streambed scour and fill to changes in the resistance to flow, which were accompanied by changes in sediment discharge. Furthermore, a simple increase in velocity at a cross section did not necessarily mean that scour would occur because adjustment had to be made for the rate of delivery of sediment from upstream.

Emmett and Leopold (1963) established closely spaced cross sections on three perennial southwestern streams in order to investigate longitudinal patterns of streambed scour and fill. Their data indicate that the scour-fill process occurs uniformly downstream. When part of the channel undergoes scour, the entire channel appears to undergo scour without regard to local channel characteristics.

Colby (1964), while not questioning the accuracy of their data, questioned whether Leopold and Maddock's measurements of scour and fill at cross sections could be accurately interpreted as representing scour and fill along an entire channel reach. He also questioned the appropriateness of relating changes in bed elevation to changes in resistance to flow which corresponded to changes in suspended sediment concentrations. Colby noted that scour and fill may be inconsistent at two cross sections experiencing similar flows and suspended sediment concentrations. He presented scour-fill data for the Elkhorn River, Nebraska, and the Colorado River at Lees Ferry, Arizona, which indicate that scour-fill patterns are inconsistent from one period to another and from one location in the stream to another. Colby suggested that two principles govern scour and fill. One principle is that of sediment continuity; a change in average bed elevation must be accompanied by a difference in bed material transport into and out of a channel reach. The second principle is that a predictable relationship exists between the discharge of sands (bed material) and the characteristics of the flow and available sediment.

Lane and Borland (1954) suggested that certain stream channel reaches may undergo a net fill while others are experiencing net scour. In studies of scour and fill in the middle Rio Grande River, they concluded that scour was most pronounced in narrow sections of the stream channel.

Silverston and Laursen (1976) developed a model of scour and fill in pool-rapid rivers in which the rapids behave as hydraulic controls and flows alternate between super critical and subcritical between respective rapid-pool sequences. In their model, the increase in head at the controls which occurs during increasing discharge is less than the increase in equilibrium depth required in subcritical (pool) reaches. In addition, the sediment transport capacity is non-uniform upon the initial rise in discharge and adjustments in bed elevation proceed so as to result in uniform transport capacity along the channel for an equilibrium (stable channel) discharge of bedload sediment. However, as each pool scours during rising discharge it results in non-equilibrium inputs of sediment to the next reach downstream. As a result, a section which eventually will scour, first may fill temporarily. In a river with a long, complex sequence of riffles and pools the composite effect at any one cross section may be for scour and fill to occur seemingly at random and often in several sequences, thus hiding the general trend towards scour during increasing discharge and fill during declining discharge. The process is further complicated by a complex hydrograph which may change or halt the equilibrium process. In effect, Silverston and Laursen's model indicates how Colby's (1964) principles of scour and fill can be used to explain the seemingly complex spatial and temporal patterns of scour and fill in pool-rapid rivers.

Both Silverston and Laursen (1976) and Colby (1964) suggested that scour-fill results from the condition of non-uniform flow encountered in natural channels. Colby, in fact, demonstrated that in long, straight, uniform channels (flumes) scour and fill, for all practical purposes, does not occur. The most common cause of non-uniform flow in alluvial channels is the existence of non-uniform channel geometries. Non-uniform channel geometries are often the result of repeating sequences of meanders and pool-riffles. These channel features are described above as mechanisms by which a stream achieves a balance between the least work-minimum variance laws of energy dissipation. While the tendency is for the meander and pool-riffle features to approach a regular pattern representing some sort of equilibrium channel geometry, in reality such perfect geometric regularity rarely exists. The pool-riffle pattern in any channel reach is highly variable about some average equilibrium geometry (Richards, 1976a). This condition of a quasi- or dynamic equilibrium in channel geometry is a result of many factors, such as channel controls, resulting from geologic or topographic irregularities or inputs of large organic debris, episodic inputs of sediment to the channel, unsteady, non-uniform flows and irregular temporal patterns of high flows. Non-uniform channel geometries assure that the simple exponential relationship between discharge and average channel velocity (Leopold and Maddock, 1953) will be different at different channel cross sections. Therefore, the bedload transport capacity of the stream will also be non-uniform and highly variable as a function of discharge. Temporary imbalances in the bedload sediment budget for short stream reaches can be expected to be a common, if not integral, characteristic of bed material routing in alluvial channels.

The condition of non-uniform flow and non-uniform bedload transport capacity assures the occurrence of irregular spatial and temporal patterns of channel scour and fill and bedload sediment transport during passage of a flood. Bennett and Nordin (1977) hypothesized that scour and fill and temporal variations in sediment transport may be most pronounced early in the passage of a snowmelt flood and that changes in bed elevation may become less pronounced as an equilibrium channel geometry is approached.

Andrews (1979) obtained relatively detailed measurements of scour and fill as a hydraulic adjustment to variations in discharge and sediment load for the East Fork River, Wyoming. Eleven cross sections were sounded at intervals of from one to three days throughout a spring snowmelt runoff. Significant scour was measured at six of the eleven cross sections. Four of the six scouring cross sections initially filled as discharge increased to bankfull stage, then, as discharge continued to increase above bankfull stage, these four scoured. As discharge decreased following the peak, the same four cross sections began to fill. One of these four cross sections was considered to represent a pool feature. Two of the scouring cross sections scoured progressively as discharge increased and filled as discharge decreased.

Significant fill was measured at five of the eleven cross sections. Three of the filling cross sections scoured slightly as discharge increased, then filled as discharge decreased. One of these three cross sections was considered to represent the runoff period. Andrew's data clearly showed that at any discharge during the flood some sections were scouring as others were filling and that at some other discharge the sequence was reversed.

Andrews quantified the hydraulic geometry (after Leopold and Maddock, 1953) of his cross sections throughout the flood and inferred bedload transport rates by comparing hydraulic conditions at the cross sections to the bedload transport rating curve developed at a nearby bedload trap (Leopold and Emmett, 1977). Mean velocity increased more slowly with increasing discharge in the filling sections than in the scouring section. The velocity reversal (Keller, 1971) occurred at roughly bankfull stage. The filling sections had larger friction factors than scouring sections and the exponent for the slope of the energy grade line was approximately the same for the scouring and filling cross sections. Therefore, at flows less than bankfull, the scouring cross sections (e.g., pools) had relatively low velocities, high hydraulic roughness and low bedload transport rates. As flows increased, these sections became smooth and had high velocities. Conversely, the filling cross sections (e.g., riffles) had relatively low hydraulic roughness and high velocity at flows less than bankfull. As discharge exceeded bankfull, the roughness of these sections remained essentially constant and velocities increased, but at rates less than the rate of increase in the scouring sections.

The data from Leopold and Maddock (1953), Emmett and Leopold (1963), Leopold et al. (1964), Colby (1964), and Andrews (1979) suggest that there is an interaction between bed elevation, the velocity of flow and sediment transport. Andrews' data further suggest that the simultaneous scouring and filling of the streambed over a specific reach is an integral part of sediment routing through an alluvial channel, and that riffles and pools may be the channel features simultaneously operating as scour-fill units.

In general, the literature indicates that the beds of alluvial stream channels are extremely active during periods of high streamflow. Furthermore, local changes in channel geometry affect the hydraulic condition of the flow and the capacity for sediment transport. This, in turn, results in local episodes of streambed scour and fill. Several different patterns of streambed scour and fill have been detected during the progression of a high streamflow event. In any reach of channel, some cross sections may be scouring while others are filling. In the short term, the channel bed may be described as representing a dynamic equilibrium. Over a longer time period, the elevation and slope of the channel bed and the average width, depth and hydraulic roughness of the stream channel adjust to accommodate average inputs of water and sediment from upslope.

Sediment Transport

Sediment transport in flowing water is generally divided into two components: bedload and suspended load. Bedload is defined as material moving on or near the bed and consists of the contact load and the saltation load of the stream (Vanoni, 1975). Most analytical treatments of bedload transport consider that a describable physical relationship exists between flow conditions and the rate of bedload transport (Graf, 1971). Suspended load consists of sediment transported in suspension in the flow. The physical relationship between flow conditions and the rate of suspended load transport in natural streams is not easily described. It is common, however, to determine empirical relationships between suspended sediment transport and water discharge for specific stream reaches (Linsley et al., 1975).

Inorganic particles less than 0.074 mm diameter (silt and clay) are generally transported in suspension. Particles larger than 2.0 mm diameter are generally transported as bedload. The sand size range (0.074-2.0 mm) may be transported as suspended load, bedload, or both, depending upon the conditions of the flow (Einstein, 1950).

Suspended Load

Vanoni (1975) considered the discharge of suspended sediment in streams to be a supply limited phenomenon. Nevertheless, for individual stream reaches, suspended sediment transport is often related to stream discharge. Such suspended sediment-discharge relationships show large amounts of variability both within single large runoff events and between separate large events (e.g., Renard, 1974; Linsley et al., 1975). Some of this variability is accounted for by a pronounced hysteresis resulting from higher concentrations of suspended sediments during rising flows than receding flows (Guy, 1964; Paustain and Beschta, 1979). This phenomenon may be the result of the depletion of suspended sediment supply within the channel (Paustain and Beschta, 1979). Channel-dominated suspended sediment supply systems are typical of small forested watersheds which experience little, if any, overland runoff and surface erosion (Hewlett and Nutter, 1969). In addition to the hysteresis exhibited during individual storms, Paustain and Beschta presented data which indicated a seasonal depletion of suspended sediment supply as a function of previous storm magnitudes and order of occurrence. In general, the slope of the suspended sediment concentration vs. discharge relationship decreases with the seasonal progression of storm events.

Sediment suspension results when the average vertical velocity component of the flow exceeds the settling velocity of the sediment particles. The concentration of sediment varies as a function of depth and is determined by the settling velocity of the particles and the magnitude and distribution of turbulence in the flow (Graf, 1971). In general, the logarithm of suspended sediment concentration is a linear function of the logarithm of the relative depth of flow. The slope of the relationships is a function of the settling velocity of the particles and the shear velocity (Graf, 1971). The shear velocity is an expression of turbulent intensity in open channel flow.

The concentration of sediment, c_y, in suspension at any depth, y, can be related to the concentration, c_a, at a reference depth, a, as follows (Einstein, 1964):

$$c_y = c_a \quad \frac{a}{y} \left[\frac{(d-y)}{(d-a)} \right]^z$$

where

a = reference depth

d = total depth of flow

z = slope of the logarithm of suspended sediment concentration vs. logarithm $\frac{d-y}{y}$ relationship.

Bedload

A particle of bed material will be transported when the forces of flow acting on the particle exceed the forces of gravity and friction which cause the particle to resist movement. As such, most bedload theory has evolved by assuming that a direct physical relationship exists between the size, shape and weight of bed material and the rate of bedload transport associated with any condition of flow (Henderson, 1966). However, the turbulent microstructure of flow is difficult, if not impossible, to treat analytically, as are the factors affecting the resistance of bed material to flow. As a result, the average bed shear stress, τ_o, or the shear velocity, U*, are generally used as indexes of the fluid forces acting on a bed particle. A representative particle size or settling velocity is commonly used as an index of particle resistance to flow (Henderson, 1966). Graf (1971) provides a review of the many empirical and semi-empirical bedload formulas that have resulted from a consideration of fluid forces acting on sediment particles. Thomas (1977) considered the Einstein bedload function (Einstein, 1950) to represent the state of the art in this type of "friction" bedload formula. In the simplified

Einstein bedload function, the intensity of bedload transportation

$$\Phi = \frac{q_b}{\gamma\ s\ \sqrt{g}\ (D_{35})^{3/2} \sqrt{\frac{\gamma_s - \gamma_f}{\gamma_f}}}$$

is plotted against a stability function for the bed

$$T = \frac{\gamma_s - \gamma_f}{\gamma_f} \qquad \frac{D_{35}}{S_e R}$$

where

q_b = bedload transport rate in dry weight of a sediment/ unit width of channel/unit time

γ_s = specific weight (weight per unit volume) of the solids

γ_f = specific weight (weight per unit volume) of the fluid

g = acceleration due to gravity

D_{35} = representative grain diameter (size by sieving such that 35% of the bed particles are finer)

S_e = energy gradient for the flow

R = hydraulic radius with respect to the bed

Einstein (1944, p. 21) interprets his two functions as follows: "Φ can be interpreted as the ratio of the velocity $\frac{q_b}{(\delta_s - \delta_f)\ g^D}$ the bed load would have if it moved down the river as a solid layer of the thickness D (grain diameter), divided by the settling velocity $\sqrt{g^D \frac{\delta_s - \delta_f}{\delta_f}}$ of the sediment particle in water.

Ψ can be interpreted as the ratio of the weight of the grain $(\delta_s - \delta_f)\ g\ D^3$ divided by the friction of the flow $\delta_s S_c R_b D^3 g$ acting on the portion of the bed covered by the particle. (Disregarding certain numerical constants of the order of magnitude equal to one, which must be determined as statistical averages.)."

Einstein's general bedload function (Einstein, 1950) includes terms to describe the fraction of total transport in a given grain size range and the fraction of bed material in a given grain size range. Also included is a method to determine a reference grain size for a particular bed, a correction factor for velocity with smooth-rough transition boundaries, a hiding factor, or correction of effective flow for various grains, and a correction for life force in transition between smooth and rough grains. The result is that the bedload function will predict a particle size distribution of bedload in transport different from that of any portion of the bed.

Another more recent approach to the problem of describing bedload transport as a function of flow is to relate bed material transport to the time rate of expenditure of potential energy of the stream (Bagnold, 1968; Yang and Stall, 1974).

Despite the rigorous development of bedload transport theory and the complexity of the bedload transport models, it is generally believed that the models are of questionable accuracy when applied to natural streams (Vanoni, 1975). In natural streams complex interactions between the hydraulic conditions of the flow and channel geometry and bedform invalidate assumptions of uniform flow. In addition, flows may be unsteady and bedload sediment supplies may be limited. For example, studies by Milhous and Klingeman (1971) and Haddock (1978) indicate that sediment supply and bed processes limit sediment availability and result in bedload transport rates which are less than those predicted by traditional bedload transport models.

Bedload Sampling Techniques

The instream measurement of bedload transport is considered to be highly dependent upon the type of measuring device utilized (Graf, 1971; Milhous and Klingeman, 1971; Emmett, 1979; Edwards, 1980). Bedload transport rates are usually measured with either basket-type samplers or pit-type samplers (Graf, 1971). Basket-type sampling involves the placement of a sampling basket onto the stream bed. The basket has some sort of mesh which will allow coarse sediment particles to be trapped while allowing passage of water and suspended-size sediments. The Helley-Smith pressure difference bedload sampler (Helley and Smith, 1971) is probably the most commonly used basket-type sampler. Emmett (1979) determined that the Helley-Smith sampler has near 100% sampling efficiency for particles from 0.5-16 mm when compared to a vortex-type pit sampler. Sampling problems exist with the sampler, however, because of rapid temporal variation in bedload transport rates and apparent great variability in transport rates across a given cross section. In addition, the clogging of pores in the sampler mesh by fine sediments and organic material may result in back pressures at the sampler orifice and consequent undersampling. Beschta (Oregon State University, Corvallis, Oregon, personal communication) tested the sampler in a flume with sand-sized (0.2-4 mm) particles in transport and found that sampling efficiency could be maintained at near 100% by a three-fold increase in the surface area of the sample bag which reduced clogging problems.

Pit-type samplers involve the insertion of some type of pit or depression across the streambed in which bedload sediments will be trapped. A vortex-type sampler has been utilized for several bedload studies in mountain streams (Milhous and Klingeman, 1971; Hayward and Southerland, 1974; Edwards, 1980). A vortex sampler involves the placement of a slit into the streambed. The top of the slit is flush with the stream bed. Discharge through the slit removes the bottom layer of water and sediment from the stream. Sediment is subsequently trapped in some sort of settling box. Klingeman and Milhous (1970) indicated the vortex sampler is 100% efficient for particles greater than 7.6 mm diameter, but substantially less efficient for sediments in the sand size range. Edwards (1980) also found the vortex sampler to be inefficient in the sand size range. Emmett (1979) assumed 100% trapping efficiency of bed material for the streambed slit-conveyor belt sampler on the East Fork River, Wyoming.

Settling basins have been used to measure long-term (storm period or greater) volumes of bedload export from a study basin. While guidelines exist for sediment basin design (Hanson, n.d.), trap efficiencies are rarely 100%. Settling basins have often been used in bedload budget studies.

Bedload Rate Studies

A number of studies have measured bedload transport rates as a function of stream discharge. No standardization exists, however, in sampling method or sampling frequency.

An early in-stream study of bedload transport using a pit-type sampler was conducted by Einstein (1944) in Mountain Creek, South Carolina. Bedload formulas which express transport rates as a function of discharge and sediment characteristics were found to adequately describe average measures of bedload transport. Very little change in bedload composition or size was found as a result of changes in rates of bedload transport.

Milhous and Klingeman (1971, 1973) conducted studies of bedload transport rates at Oak Creek, a heavily armored stream in the Oregon Coast Range. A vortex-type bedload sampler was used. At flows greater than the critical flow required for armor disturbance bedload transport was shown to increase logarithmically as a function of discharge. The peak bedload transport rate measured was approximately 450 kg/hr at a discharge of 2.0 m^3s. The relationship between discharge and bedload transport changed following an extremely large flow which resulted in a decrease in the critical discharge required for armor disturbance. The discharge of cobbles and sand was higher during the rising limb of the hydrograph and the discharge of gravels was higher during the falling limb of the hydrograph.

Heinecke (1976) continued the bedload sampling program at Oak Creek. The simplified Einstein bedload function was shown to overestimate bedload transport rates. Flows sampled, however, were comparatively small. Maximum bedload transport rates were approximately 265 kg/hr at a discharge of 2.1 m^3/s.

Nanson (1974) used a basket sampler to measure bedload transport in Bridge Creek, Alberta, Canada. Bedload rates as high as 6,000 kg/hr at a discharge of 1.08 m^3/s were measured. Bedload transport rates as a function of discharge were higher on the rising limb of the discharge hydrograph than the falling limb. As in the Milhous and Klingeman study, the critical discharge for incipient bedload transport changed following the discharge peak--in this case increasing.

Hayward and Southerland (1974) used a vortex-type sediment trap to measure bedload transport rates in a New Zealand stream over five days during high snowmelt runoff. Seventy-eight thousand kilograms of bedload were discharged over five days. Intensive sampling over a three-hour period (stream discharge approximately constant at 9.37 m^3/s) indicated variations in bedload transport rates from 150 to 4,560 kg/hr. The authors concluded that bedload transport was a very unsteady phenomenon dependent upon other factors in addition to streamflow.

Edwards (1980) used a vortex sampler and a Helley-Smith sampler to measure bedload transport in a sand and gravel bedded stream in the Oregon Coast Range. Edwards found large temporal variations in bedload transport at a single point on the stream and large variations in transport between different stream cross sections. In one storm in February, 1979, bedload transport rates varied between 20 kg/hr and 105 kg/hr. Peak stream discharge was roughly 1.5 m^3/s. Bedload discharge exhibited several distinct peaks during the falling limb of the hydrograph. The median size of the bedload material was essentially constant over time, ($d_{50} \approx 0.4$ mm), but the d_{90} size increased significantly during bedload discharge peaks (from 1.0 to 5.0 mm).

Johnson and Smith (1977) sampled bedload sediment transport with a Helley-Smith sampler on Reynolds Creek in southwestern Idaho. Infrequent samples taken during three separate annual snowmelt runoff periods measured maximum bedload discharge rates of approximately 300 kg/min-m at the stream center. Rates at the center of the stream were as much as 60 times greater than those one-quarter distance to the center. A linear relationship existed between the logarithms of streamflow and bedload discharge at the stream center. The mean particle size in transport was shown to increase logarithmically with discharge. Measured bedload transport rates were much less than those predicted using the formula developed by Schokletsch (1934).

Haddock (1978) used a Helley-Smith sampler to sample bedload transport rates on three streams of the Colorado Front Range. The streams were sampled during spring runoff over a three-year period as often as daily, but generally at lesser frequencies. Multiple linear regression equations were developed which related bedload discharge to water discharge and drainage density. Comparison of measured bedload rates to those predicted by the Schokletsch and the Meyer-Peter-Müeller equations indicated that the bedload equations significantly overestimated bedload transport rates. It was concluded that the streams studied were supply limited with regard to bedload transport.

Bjornn et al. (1977) used a Helley-Smith sampler to measure bedload transport during the spring, 1974, snowmelt runoff on three streams at six locations in the Idaho batholith. Sampling intervals corresponded to changes in the discharge hydrograph (daily or less frequently). During the 1975 runoff period, the streams were sampled daily, with sediment transport rates through pools compared to those at riffles, and rates at the upstream edge of a riffle compared to those at the downstream edge. In general, Bjornn et al. found that bedload transport rates peaked prior to the discharge hydrograph and then decreased due to limited bedload supply. Maximum discharge rates corresponded to those predicted by the Meyer-Peter-Müeller equation. Measured sediment transport through pools was less than that over riffles but the authors questioned the reasonableness of their data. In addition, cumulative bedload transport at the upstream end of a riffle was higher than that at the downstream edge. The spatial variations in bedload transport were not explained because data were insufficient to detect changes in sediment storage on the riffle.

Emmett (1976) sampled bedload transport using a Helley-Smith sampler in the Snake and Clearwater Rivers near Lewiston, Idaho. The two cross sections were visited approximately weekly during the 1972-1974 spring snowmelt runoffs. Sampled bedload rates were compared to flow conditions as expressed by the unit stream power (Bagnold, 1966). A different relationship was found at high stream power where the stream was competent to transport all bed material particle sizes than at lower stream powers where bed armoring progressively limited the availability of bed material for transport. Emmett also noted that bedload transport at flows less than those required to disrupt the armor layer involved mostly sand sized sediments, whereas principally coarse gravel sized sediments were transported at flows competent to disrupt the bed armor. In effect, Emmett was the first to suggest the existence of two distinct phases of bedload transport in armored channels.

One of the most intensive on-going programs of bedload transport measurement is being conducted on the East Fork River in Wyoming (Leopold and Emmett, 1976; Mahoney et al., 1976; Leopold and Emmett, 1977; Emmett, 1979). A conveyor belt, pit-type bedload sampler has been installed as the principal bedload sampling device and the device with which Helley-Smith samples are calibrated and sediment discharge rating curves are developed. In addition to the conveyor belt sampler, numerous upstream cross sections have been regularly monitored for bedload transport, scour and fill and hydraulic conditions (Andrews, 1979). Mahoney et al. (1976) summarized bedload transport data. A model of bedload transport for the East Fork River was developed by Bennett and Nordin (1977). In general, bedload transport in the East Fork River, which is predominantly a sand bedded river, is described as a non-steady state process with considerable fluctuations in bedload transport rates both temporally and spatially. Spatial fluctuations exist both across the stream and along the stream. Longitudinal fluctuations in bedload transport appear to be related to streambed scour and fill (Andrews, 1979). Leopold and Emmett are currently preparing an interpretation of the bedload transport data for the East Fork River (Emmett, 1979).

Bedload Budget Studies

Over a time scale of at least decades or centuries, a stream which is experiencing no net aggredation or degredation of its channel transports as much sediment past a point as is delivered to the channel upstream. On an annual time scale, however, such a sediment balance may not exist and the stream may experience temporary localized deposition or scour of sediments. The three variables--sediment delivery, sediment export and sediment storage--thus form the basis for a sediment budget for a given channel reach.

In western Oregon, annual sediment budgets were prepared for three small watersheds in the H. J. Andrews Experimental Forest (Fredriksen, 1970). The mean annual bedload discharge was

16.3 tons/km for a forested watershed and 39 tons/km^2 for a clearcut watershed with no roads over a six-year period. Total mean annual sediment discharge was 32.3 tons/km^2 and 106.7 tons/km^2, respectively, for these two watersheds. A third watershed which was roaded and patch cut had a mean annual bedload and total load discharges of 2,276 and 2,773 tons/km^2, respectively, over a nine-year period.

Dietrich and Dunne (1978) deduced a long-term equilibrium sediment budget for Rock Creek in the Oregon Coast Range. They concluded that the ratio of bed material storage in the channel to annual bedload transport is very large and that small changes in storage could have large effects on sediment discharge. Using a sediment mass balance, they estimated the channel residence time for sediment in Rock Creek to be approximately 619 years, and approximately 31 years for gravel bar sediment.

In the Alsea Watershed Study (Moring, 1975a) gravel erosion and deposition were measured over a ten-year period in three small streams in the Oregon Coast Range. The data indicated no net channel erosion or deposition over the time period, but did show considerable variability on a year-to-year basis. Kelsey (1977) prepared a sediment budget and studied sediment routing in the Van Duzen River Basin in northern California. Large pulses of sediment in 1964 caused aggradation of headwater channels in two basins. The sediment pulses were routed downstream at rates varying between 8.9 km/10 years and 13.7 km/10 years.

Interactions between Stream Flow, Sediment Transport and Streambed Composition and Form

A large number of sediment transport factors are highly variable as a result of the interactions between flow conditions, sediment transport and streambed composition and form. These factors include: (1) particle sorting due to discrepancies between size gradation of material in transport and material on the bed; (2) variations in hydraulic radius and roughness due to changes in bed composition, bed form and sediment in transport; (3) temporal variations in the availability of bed material for transport under given flow conditions due to temporal variations in bed material size; and (4) longitudinal variations in bed material size and longitudinal variations in channel geometry and the properties of the flow.

Most theories of bedload transport describe the transportable bed material in terms of a representative particle diameter (Graf, 1971). Einstein (1964), with the introduction of the hiding factor, showed that particle size gradation is an important factor in determining the availability for transport of particles in a specific size range. Other researchers indicate non-uniform particle size distributions in bed material influence the availability of sediments for transport. Laursen (1958), for example, presented a transport relation which predicts that the gradation of bedload material in transport will be finer than that in the bed. Renard (1974) stated that the rate of bedload transport is particularly sensitive to the finest fraction of the bed material since it is the most easily transported. Bagnold

(1968) noted that bedload transport may favor intermediate particle sizes when the source is a non-graded mixture. Kellerhals (1967) described flume experiments with sediments of a wide range of grain sizes and demonstrated the selective nature of the flow to certain size classes and the sorting of grain sizes upon sediment deposition. Furthermore, Milhous and Klingeman (1973) proposed that the armor layer in a coarse bedded stream is an important regulator of supply for bedload and suspended load transport and that the characteristics of the armor layer vary as a result of sediment transport conditions during large flows.

Laronne and Carson (1976) showed that the resistence of bed material to fluid drag is increased due to the interlocking structure of the bed made possible by the broad range of particle sizes comprising the bed, and by the shape of the sediment particles. The treatment of stream competence as a simple function of sediment particle weight and channel hydraulics was shown to be inadequate in describing bed material mobility.

Bedforms, in addition to individual particle roughness, contribute to the overall resistence to flow in open channels by influencing the effective value of hydraulic radius (Einstein, 1964). Bedforms are highly variable and a function of flow in sand bedded streams (Graf, 1971).

Sediment in transport contributes to an effective decrease in hydraulic roughness as expressed by Manning's "n" by decreasing the magnitude of turbulent fluctuations near the bed with the resulting decrease in dissipation of stream energy through turbulent mixing (Vanoni, 1941; Einstein, 1944; Leopold and Maddock, 1953). The higher average velocities associated with reductions in hydraulic roughness, combined with the increase in fluid density due to sediments in suspension may result in the increased capability of the flow to transport bed sediments and scour the bed surface (Leopold and Maddock, 1953; Yalin and Finlayson, 1972; Andrews, 1979).

Dietrick et al. (1979), in a study of sand transport in meander bends, demonstrated that small bedforms such as ripples and dunes interact with the flow to cause localized areas of increased bed shear stress in the troughs of bedforms. Rates of bedload transport were shown to be higher in areas of increased bed shear stress.

Bedload Transport: Dynamic Bed Models

The nature of the interactions between the flow hydraulics, sediment transport, and streambed composition and form in natural sreams is extremely complex. Several authors, however, have suggested that bedform dynamics--particularly scour and fill--may be predictable processes which are closely related to the bedload transport process (Leopold and Maddock, 1953; Emmett, 1976; Schumm, 1977; and Andrews, 1979). Kellerhals (1967) and Renard (1974) suggested that the composition of the streambed is another variable in the bedload transport-scour-fill interaction.

Bennett and Nordin (1977) indicated that a successful sediment transport model must utilize three basic components. The first computes a time history of hydraulic conditions along a channel reach based on information about channel geometry and roughness and discharge into and out of the channel reach. The second computes sediment transport rates for known conditions of flow, bed composition and sediment inflows. The third component accounts for local changes in channel bed elevation and bed material size composition.

Two models (Bennett and Nordin, 1977; Thomas, 1977) were reviewed which calculate bedload transport rates as a function of hydraulic conditions, sediment inflows and streambed scour and fill. A third model, based upon similar principles, is being developed by Hydrocomp, Inc., for the Environmental Protection Agency (Johanson and Leytham, 1977). The Thomas Model was developed for the U.S. Army Corps of Engineers to analyze net scour and deposition in rivers and reservoirs. Bennett and Nordin (1977) developed a model to describe sediment transport and scour and fill through a specific reach of the East Fork River in Wyoming during a spring snowmelt runoff.

The Thomas Model uses steady, non-uniform flow backwater computation techniques to compute the hydraulic variables. Toffaleti's version of the Einstein bedload function (Toffaleti, 1966) or Laurson's transport relationship (Laurson, 1958) is used to calculate bedload transport rates. Scour and deposition occur as a result of a mass imbalance resulting from differences in sediment input and sediment transport capacity. In contrast, the Bennett and Nordin

Model uses an unsteady flow computation to compute hydraulic variables. Bedload transport rates are computed by the DuBoys method (Graf, 1971). Like the Thomas Model, changes in bed composition and elevation occur as a result of differences in sediment input and sediment transport capacity over a finite length of stream channel. The models differ somewhat in the method of defining the bed composition and armoring function and the effects of non-uniform sized mixtures of bed material on bedload transport rates.

Thomas Model

The Thomas Model is designed to analyze scour and deposition in rivers by considering the interaction between the hydraulics of flow, sediment transport, and the sediment material comprising the stream bed. In addition to embodying the factors considered in the Einstein bedload function, the model provides for the formation and destruction of the armor layer and the aggredation and degredation of the streambed. No provision is made for the consideration of bedforms or of streambank scour or deposition.

A continuity equation for sediment material (the Exner equation) is expressed in finite difference form and is the basis for the simulation of scour and deposition on the streambed:

$$\frac{\partial G}{\partial x} + B_o \frac{\partial Y_s}{\partial (DD)} = 0$$

where:

G = sediment load in ft^3/day

DD = time in days

Y_s = depth of sediment deposit above model bottom

X = distance along the channel

B_o = width of deposit (moveable bed)

Hydraulic parameters necessary for the calculation of sediment transport include velocity, depth, width and slope of the energy grade line. These parameters are determined from the calculation of water surface profiles using standard step methods for steady, non-uniform flow. Sediment transport capacity is calculated from Laursen's transport relationship (Laursen, 1958) or Toffaleti's version of the Einstein bedload function (Toffaleti, 1966) but is modified by a bed composition and armoring routine.

The bed composition and armoring routine presented by Thomas (1977) involves: (1) determining an equilibrium depth of flow for bed stability for a given grain size and unit discharge; (2) calculating depth of scour in a bed composed of a mixture of grain sizes to accumulate a sufficient amount of coarse material to armor the bed (or to obtain an equilibrium depth of flow); and (3) determining the stability of the armor layer.

The equilibrium depth of flow for uniform grain sizes is calculated by simultaneously solving Manning's, Streckler's, and Einstein's equations:

$$D_e = \left[\frac{q}{10.21\ d^{1/3}}\right]^{6/7}$$

where:

D_e = water depth for the condition of no transport

q = unit of discharge

d = sediment particle diameter

The armoring function can be conceptualized by considering a column of bed material composed of a mixture of grain sizes with a surface area, SA (Fig. 4).

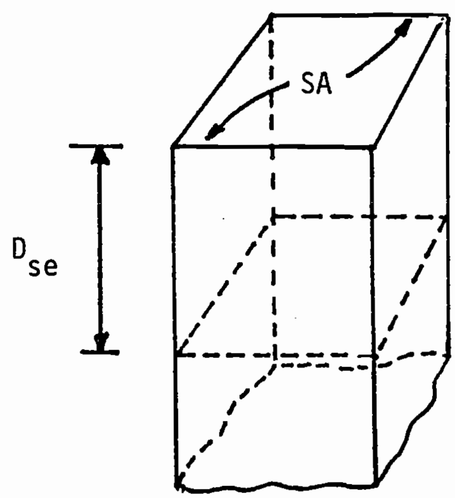


Figure 4. Column of bed material (from Thomas, 1977, pp. 3-15)

The number of grains, N, of particle size, d, required to completely shield the surface area, SA, is:

$$N = \frac{SA \quad SAE}{\frac{\pi d^2}{4}} .$$

where SAE is the ratio of the surface area of potential scour to total surface area and is represented by the ratio of the volume of material scoured from an active bed zone to the total volume of the active bed. The active bed zone is, in turn, defined as the zone from the bed surface to the equilibrium depth. Equilibrium depths for a bed composed of a mixture of grain sizes must be determined iteratively by comparing the equilibrium depth for uniform mixtures (equation 1) to the depth of scour required for each particle size class to achieve 100% armoring.

Bedload transport equations are applied by multiplying the transport calculated for a given size fraction of bed material by the fraction of the bed comprised of that material size. Transport rates calculated in this manner are further reduced by the influence of armoring. Einstein's bedload function accounts for the influence of armoring by use of the hiding factor. Laursen's transport relationship must be corrected for the effects of armoring. If the transport capacity exceeds sediment discharge, scour occurs. Conversely, if sediment discharge exceeds transport capacity, deposition occurs. The Thomas Model was applied to the Alchafalaya floodway of the Mississippi River in Louisiana for the period 1963-1973 (Amar and Thomas, 1976). Model calibration was performed and theoretical bi-annual calculations of water surface elevation and cross section profile were compared to actual observed values. In general, the model accurately predicted water surface elevation and cross section area but did not accurately predict the geometry or elevation of the channel bed. Clay, silt and sands were the sediments in transport.

Bennett and Nordin Model

The Bennett and Nordin Model was developed to describe sediment transport and scour and deposition in the East Fork River of Wyoming during spring snowmelt runoff. This model incorporates (1) an unsteady, non-uniform flow computation component, (2) a routine to calculate rates of bedload and suspended load transport, (3) a means of determining transitions in the mode of transport between suspended load and bedload as a function of the flow and sediment transport conditions, and (4) a bed armoring and scour-fill routine.

The unsteady flow computation component is that presented by Bennett (1975) and is used to determine the required hydraulic variables for the sediment transport equations. The authors state that steady non-uniform backwater techniques may be used under certain conditions.

This model utilizes a continuity equation for bed sediment material similar to that used by Thomas (1977). The principal difference is that the Bennett and Nordin continuity expression is not set equal to zero, but is set equal to "S", a source term for the transfer from the suspended sediment zone into the bedload sediment zone. A continuity equation for suspended sediment material is also set equal to the "S" term.

Bedload transport is determined from local hydraulic conditions by use of DuBoys equation (Graf, 1971). Since the DuBoys equation is determined for flow over beds of uniform composition, a correction parameter is defined for transport for a particular size material within a bed comprised of non-uniform size material. This correction parameter is adjusted during model calibration.

The model requires continuity in sediment concentration across a hypothetical suspended load-bedload boundary. A model of equilibrium sediment concentration profiles is utilized to determine the suspended sediment concentration at the suspended load-bedload boundary under given conditions of flow and sediment transport. A sediment concentration imbalance at the hypothetical boundary sets up a sediment flux in the direction of the lowest concentration and the relative suspended load-bedload transport is corrected as a function of a downstream distance increment.

A bed composition accounting routine keeps track of the size composition and elevation of the bed at the discrete cross sections used to represent the stream reach in consideration. Bennett and Nordin define an active layer which represents the bed material layer which can be "worked" by the water in a finite time increment. The thickness of the active layer is defined by a parameter "n" times the d_{50} of the largest bed material size. The value of "n" must be determined in model calibration. The composition of the active layer is a function of initial conditions and the cumulative effects of scour and fill. The model considers that sediment transport in a size fraction is limited to the amount of material of that size in the active layer (supply limited) or by the transport capacity of the flow (capacity limited). As stated above, the effect of armoring or non-uniform bed material size on transport capacity is handled by the correction factor term in the DuBoys equation.

Scour of the bed occurs when bedload sediment transport conditions at the cross section, whether supply or capacity limited, exceed an influx of sediment from upstream and from the suspended sediment transport. Neither the frequency nor duration of sediment transport and bed elevation sampling was sufficient to adequately calibrate the Bennett and Nordin model or to assess the accuracy of its results.

In general, bedload transport studies indicate temporal and spatial variability in bedload transport rates at a given level of discharge. Bedload transport rates in steep mountain streams and in gravel bedded alluvial streams are controlled not only by the transport capability of the flow but by the availability of transportable bed material. The supply of bed material may be limited either by processes of sediment delivery to the channel or by the mechanics of bed material routing through the channel and the particle size gradation of bed sediments. A successful sediment transport model must be able to calculate bedload transport rates as a function of hydraulic conditions, sediment inflows and streambed scour and deposition. As such, it must incorporate components which accurately account for streambed elevation and composition. Few quantitative or descriptive models exist of the routing of sediment through a channel reach and there are no unifying explanations of the often contradictory results of existing bedload transport measurements. At present there is little information which would enable one to determine the particle size composition of bed material resulting from net deposition during the transport of a mixture of bed material sediment sizes. Very few field data exist which would permit the calibration or verification of transport models associated with dynamic streambeds.

Substrate Gravel Composition

Spatial and Temporal Variability

The overall composition of a stream channel reflects the long-term integration of the geology, geomorphology, biology, climate and hydrology of the drainage basin (Schumm, 1961). However, within a single stream the composition of streambed gravels--particularly with regard to the percent fine sediment (< 1 mm) within the gravels--may be variable both in space and time (Smedly et al., 1970; Platts, 1974; Renard, 1974; Platts and Megahan, 1975; Tagart, 1976; Corley, 1978; Adams, 1979; Shirazi and Siem, 1979). Variability exists both horizontally and vertically in gravel composition at a given location. Over time the scour and redeposition of bed materials and the deposition and intrusion of fine sediments result in changes in substrate composition (Meehan and Swanston, 1977; Adams, 1979; Shirazi and Siem, 1979). Channel, watershed and hydrologic conditions which affect the conditions of streamflow, sediment delivery, sediment transport and bed mechanics (scour and fill), and which affect the rate and extent of sediment intrusion are factors which affect the extent of the short-term variability in substrate composition (Cooper, 1965; Bennett and Nordin, 1977; Thomas, 1977; Beschta and Jackson, 1978).

Adams (1979) sampled stream substrates using a frozen core device on 21 watersheds in the Oregon Coast Range in order to describe variability between streams in the percent of fine sediment (< 1 mm) in the stream substrates and to attempt to correlate substrate composition with key watershed and land use characteristics. Statistically significant ($p = 0.95$) differences existed in substrate composition between watersheds. Watershed slope, area, relief, and land use characteristics were all significant variables in accounting for differences in substrate composition between streams. Significant differences ($p = 0.95$) also existed in substrate composition at different locations within a single stream. Hydraulic conditions represented by channel sinuosity and bankfull stage were significant variables in accounting for within-channel differences.

Adams also sampled 13 streambeds in five streams in order to detect variations in substrate compositions over time. Seven of the 13 streambeds sampled showed a decrease in fine sediments over the winter high flow season. Adams suggested that the decrease in fines occurs during high flow events and occurs in only localized areas of the stream. Small storms were thought to be more effective in decreasing fine sediment concentrations in the substrate than large storms.

Adams suggested that the amount of fine sediment in transport at the time of gravel deposition is an important factor in determining the composition of the substrate.

Cedarholm and Salo (1979) reported on the composition of stream-bed gravels sampled over a six-year period from streams on the Olympic Penninsula in Washington. The samples were collected in order to assess the effects of a landslide on downstream spawning areas and to detect relationships between gravel composition and land use. They found an increase from 8.36% to 10.09% in percent fine sediment (< 0.85 mm) in Stequaleho Creek in gravels affected by the landslide and an increase from 8.30% to 9.12% in gravels in the Clear-water River below Stequaleho Creek. In addition, the percent fine sediment in gravels correlated positively ($p = 0.99$) with the percent of subbasin clearcut, miles of logging road per basin square mile, or percentage of basin in roads. High gradient streams were shown to be efficient in flushing fine sediments, but lower gradient streams were shown to retain sediments over longer periods of time.

Platts and Megahan (1975) evaluated the size of riverbed surface materials at closely spaced cross sections in four major spawning areas during an eight-year period in the upper half of the South Fork Salmon River, Idaho. The spawning areas had been damaged prior to the sampling period by severe floods and excessive sediments due to land use activities. The sampling period corresponded to a period of reduced erosion and sediment delivery to the stream. Surface sediment composition changed significantly over the sampling period; the percent of fine sediment decreased and the percent gravel and rubble increased.

Heinecke (1976) reported on bed material sampling on Oak Creek in the Oregon Coast Range. He showed temporal and spatial variability in the composition of both armor gravels and sub-armor sediments. Milhous and Klingeman(1971) indicated that armor size varies in response to storm history and bedload transport.

Tagart (1976), Platts (1974) and McNeill and Ahnell (1964) all reported a high degree of variability in gravel composition between samples taken of salmon spawning redds during studies of salmonid survival.

A number of researchers have reported increases in the percent of fine sediments in streambed gravels following various land-use activities which were believed to increase the rate of delivery of sediments to the channel. Saunders and Smith (1965) reported a temporary increase in fine sediments in streambeds on Prince Edward Island, Alaska, which they attributed to erosion from areas of road construction and timber harvest. Sheridan and McNeil (1968) reported temporary increases in fine streambed sediments due to road construction and road-related landslides. Burns (1970) attributed measured increases in fine sediments in spawning gravels in four California streams to road construction activity near the streambanks or in the channels. Moring (1975a) reported a significant increase in fine sediments in spawning gravels following logging on Deer Creek in the Oregon Coast Range.

Physical Processes Affecting Substrate Gravel Composition

Two principal processes contribute to variability in substrate gravel composition. First, fine sediments in transport in suspension or as bedload may intrude into the pore spaces of a stable gravel substrate with a subsequent increase in the fine sediment composition of the substrate (Cooper, 1965; Beschta and Jackson, 1978). Second, conditions during the initial deposition of the substrate gravel matrix may result in variations in the sediment size composition of the gravels (Thomas, 1977). The term gravel "flushing" appears to be associated with a process of scour and redeposition of streambed gravels with a resultant decrease in the amount of fine sediments in the gravels. The removal of fine sediments from a stable gravel substrate has not been shown to be an important process in streams. "Silting" of a gravel bed is a term applied to either an increase in the fine sediment composition of a gravel substrate resulting from intrusion or redeposition processes, or the deposition of fine sediments upon a stable gravel substrate.

Studies of the intrusion of fine sediments into a stable gravel substrate have been performed in both controlled experiments (flumes) and in natural streams. Cooper (1965) conducted intrusion experiments in a flume in order to investigate changes in gravel permeability as a function of suspended sediment size, concentration and duration of flow over a stable gravel bed. He defined gravel permeability in terms of particle size grading, particle shape and gravel porosity and demonstrated reductions in permeability due to the deposition of fine sediment on or within the gravels. Cooper showed that the relative rate of removal of sediment from the water could be expressed as follows:

$$\log \frac{r_o - r_t}{r_o} = \frac{-y}{(ct)^x}$$

where:

r_o = initial rate of removal of suspended sediment

r_t = rate of removal at time, t

c = suspended sediment concentration in ppm

t = time in minutes

x,y = factors related to sediment concentration

Results of the tests showed gravel permeability to decrease in proportion to the rate of suspended sediment removal (intrusion). Removal rates were essentially constant over time when suspended sediment concentration was maintained at a constant level. Removal rates did not vary as a function of flow velocity. Cooper concluded that settling velocity of silt particles was the main factor influencing suspended sediment removal. Gravel sizes affected the efficiency in the ability of deposited silts to decrease permeability. The permeability of finer gravels decreased faster than that of coarser gravels.

Einstein (1968) also studied the deposition of suspended sediments into a stable gravel bed in a recirculating flume. Two sizes of gravel beds were used, with two different bed thicknesses for each bed size. Two flow velocities were also tested. It was concluded that the deposition of silt particles in the gravel occurred from the bottom up. The rate at which the particles settled out of suspension was proportional to the concentration near the bed which in turn was proportional to the settling velocity of the particle. Einstein's integrated expression for the reduction in sediment concentration over a gravel bed is:

$$\ln c_o - \ln c = \frac{V_s t}{d}$$

where:

c_o = initial suspended sediment concentration

c = concentration at time, t

V_s = settling velocity of sediment size in question

d = depth of water

The effects of gravel size and flow velocity were not analyzed, but Einstein implied that they influence intrusion rates by affecting the concentration profile of.suspended sediment and thus the sediment concentration near the gravel surface.

Beschta and Jackson (1978) used a flume to investigate the intrusion of sand sized sediments into a stable gravel bed (d_{50} of gravels = 20 mm). They concluded that the particle size of the sediment was an important factor affecting the intrusion process. Fine sands (d_{50} = 0.2 mm) intruded freely into the gravel bed and filled the gravels from the bottom up. Larger sands (d_{50} = .05 mm) were trapped in gravel voids near the surface and eventually formed a barrier to further intrusion. The extent of intrusion was believed to be affected by the rate and depth of formation of the sand seal which, in turn, may have been affected by flow conditions as indexed by the Froude number.

Garvin (1974) used a flume to study the intrusion of organic logging debris into stable gravel beds under conditions of low and high flow. For low flow conditions, organic material size class and gravel pore volume were found to be significant variables affecting the weight of organic material per volume of gravel bed. Under high flows, the gravel bed became unstable and moved in layers with no vertical mixing of particles.

Garvin (1974) also summarized three processes by which particles can be collected in a stable porous medium: gravity settling, sieving, and interception. Particles are believed to leave the flow above a stable bed by settling under the influence of gravity. The nature of the settling is affected by flow and fluid characteristics and by particle characteristics such as specific weight and shape. Once particles have settled into the relatively placid intergravel environment they are subject to interception by a horizontal gravel surface or filtering by gravel pores. In soil mechanics, filtering has been shown to be a predictable interaction between filter size in relation to sediment size and gradation (Sowers and Sowers, 1970).

Meehan and Swanston (1977) indicated that gravel shape is a factor affecting the intrusion rate of fine sediment. At low flows round gravel accumulated more sediment than flatter or more angular gravels. At high flows the results were reversed and angular gravels accumulated more sediments.

Cedarholm and Salo (1979) reported on a project in which sediment intrusion monitors were buried in natural stream gravels above and below an area affected by landslides. Monitors downstream of the landslides collected almost three times as much intruded sediment as monitors upstream of the landslides.

Ringler (1970) detected a seasonal increase in fine sediments in individual spawning redds in natural channels in the Oregon Coast Range. Presumably the intrusion process affected the gravel composition.

Not all studies indicate that intrusion of fine sediments into stable streambed gravels will occur. For example, Bjornn et al. (1977) added fine sediments to a natural stream but did not detect an increase in fine sediments in riffle gravels. The fine sediments, instead, deposited in deep pools resulting in varying levels of imbeddedness of pool cobbles.

The change in stream substrate composition resulting from the deposition of bedload sediments or from the scour and redeposition of bed load sediments is a phenomenon which has been detected in natural streams but which has not been rigorously studied (Bagnold, 1968). A number of investigations mentioned previously in this report detected changes in gravel substrate composition following high streamflow events. Beschta and Jackson (1978) observed that removal of fine sediments from gravels only occurs if the gravel bed is moved. Adams (1979) found that reductions in the percent fine sediment composition of gravel substrates in Oregon Coast Range streams often corresponded to changes in elevation of the channel bed.

Sediment deposition has been studied in pipes for both uniform sediments and sediment mixes (Vanoni, 1975). The emphasis has been on obtaining a quantitative determination of a minimum velocity necessary to maintain pipes free of deposited sediments. Volumes of deposited sediments have been determined in various navigable rivers in association with dredging programs. No studies were found which examined variations in the composition of temporary channel features--such as bars--at the scale of a single high flow, or scour-fill event. In addition, no laboratory or flume studies were found which examined the hydraulics of deposition of particles from a sediment mixture or the composition of depositional features as a function of the flow condition and sediment properties at the time of deposition.

Bagnold (1966) studied the sediment transport process theoretically by applying the concepts of general physics. However, he noted a lack of theory and research pertaining to the deposition process--particularly with regard to the sediment size distributions of depositional features in relation to the flow conditions during which the deposits are laid down.

The two models of bedload transport (Thomas, 1977; Bennett and Nordin, 1977) described elsewhere in this report provide for the scour-fill and armoring of the streambed. They assume that particle deposition can be described simply as a condition of non-transport. Deposition involves those sediment particles in the flow in excess of that predicted by steady state bedload equations with empirical corrections for the effects of particle size interactions on sediment supply. To date, the validity of this assumption has not been verified in model calibration tests and does not seem to be based upon any theory of the mechanics of bedload sediment deposition.

In summary, the available literature provided a basis for hypothesizing a two-phase system of bedload transport in alluvial channels exhibiting a sequence of pools and armored riffles (e.g., Keller, 1971; Emmett, 1976). No studies were found, however, which correlated two distinct phases of bedload transport with scour-fill measurements. Both Andrews (1979) and Bennett and Nordin (1977) kept daily measures of bed elevation and either inferred or measured bedload transport rates on the East Fork River, Wyoming. However, that stretch of river was described as essentially sand bedded and apparently did not exhibit armored riffle features.

III. FIELD STUDIES

The specific objectives of the field studies were to:

1. demonstrate the hypothesized two-phase system of bedload transport in alluvial channels exhibiting a sequence of pools and armored riffles;
2. describe the timing of the two phases of bedload transport in relation to a storm hydrograph;
3. characterize bedload transport rates and particle size composition during Phase I bedload transport;
4. examine variations in bedload transport rates and particle size composition which correspond to cycles of streambed scour and fill during Phase II bedload transport;
5. measure the particle size composition of streambed gravels deposited during Phase II bedload transport and compare this to the hydraulic and sediment transport conditions corresponding to the period of streambed deposition.

Study Streams

Field measurements were made at Flynn Creek in the Oregon Coast Range (Fig. 5) during the winters of 1978-79 and 1979-80, and at Huntington Creek in central Utah (Fig. 6) in the summer of 1979. Flynn Creek was chosen because it is representative of small third-order streams in the Oregon Coast Range--a region in which sediment production associated with timber harvest is of particular concern because of its possible effects on fisheries resources. Flynn Creek was the control watershed in the Alsea Watershed Study (Moring and Lantz, 1975). In addition, Flynn Creek is the site of on-going studies of bedload and suspended load transport by the School of Forestry, Oregon State University.

Huntington Creek was utilized because it was the site of a controlled release of water from an upstream reservoir for the purpose of flushing fine sediments from downstream fish spawning gravels. The simulated storm discharge at Huntington Creek provided a unique opportunity to perform the field measurements under conditions which enabled control over the timing and magnitude of streamflow and which restricted the source of transported sediments to those already existing in the immediate stream channel. The sediment flushing project was a cooperative effort between the Manti-La Sal National Forest, the Utah Department of Fish and Game, the Utah Power and Light Company and Oregon State University School of Forestry.

Although different in size and geographic setting, both Flynn Creek and Huntington Creek have alluvial channels with beds comprised of sand and gravel and exhibiting distinct sequences of pools and armored riffles. The pool-riffle sequences are not regular. In Flynn Creek large logs serve as deflectors and small channel steps and control the location of many channel features. In Huntington

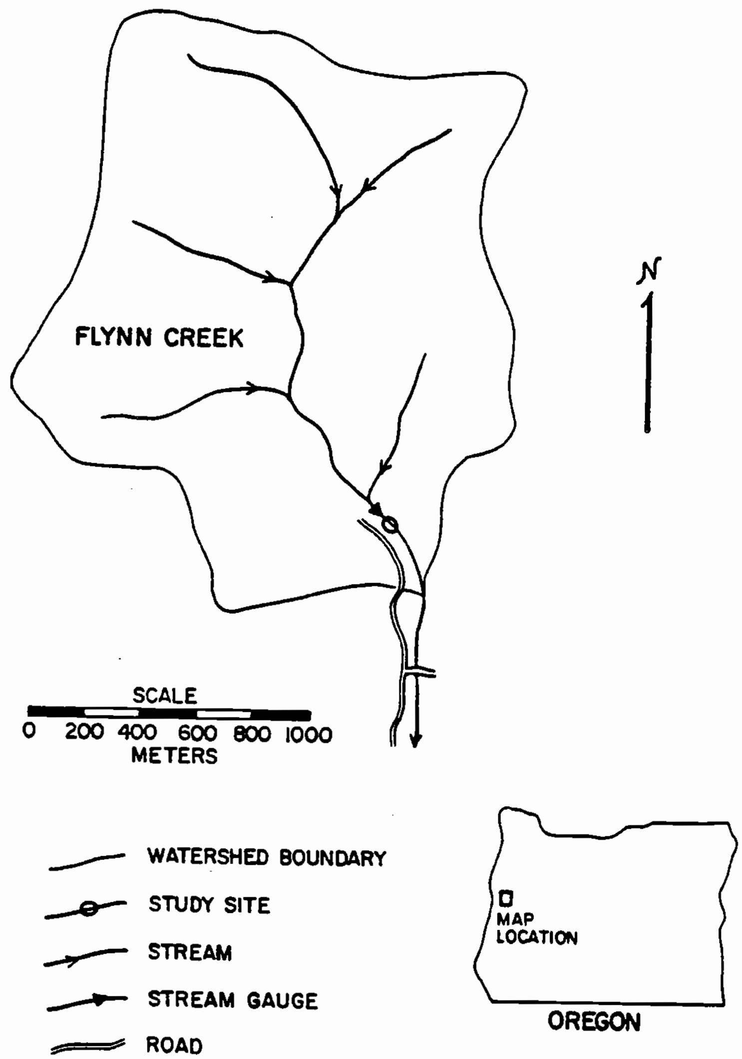


FIGURE 5. Location map of Flynn Creek, Oregon.

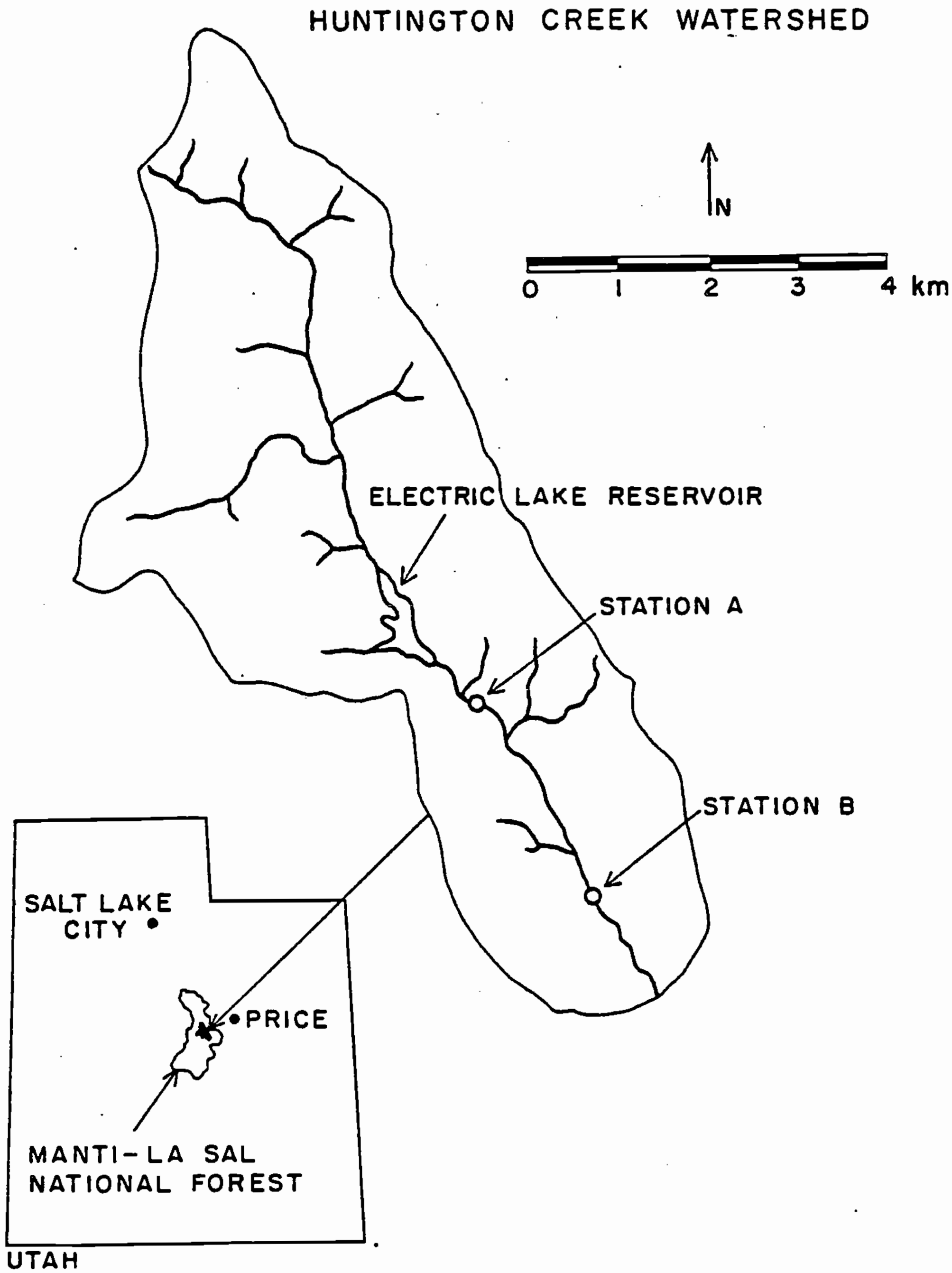


FIGURE 6. Location map of Huntington Creek, Utah.

Creek, beaver dams and rock outcroppings control the location of many channel features.

Flynn Creek is a forested second order drainage in a region of interbedded sandstones and siltstones. The watershed above the USGS stream gauge is 202 ha. Elevations range from 183-457 meters. Slopes are moderate to steep. Soils are predominantly moderate to deep gravelly loams. Overstory vegetation is Douglas fir (*Pseudotsuga menziesii*) and red alder (*Alnus rubra*). Streamside vegetation is dominated by salmonberry (*Rubrus spectabilis*) and red alder.

Precipitation averages 244 cm per year and occurs primarily as rain from November through March. Subsurface flow is the dominant process by which precipitation is routed to the stream channel. Sediment movement from upslope to the channel occurs primarily as soil mantle creep and shallow mass soil movements. The majority of sediment transport within the channel occurs relatively infrequently during periods of winter freshets.

The stream channel in the study reach averages approximately 3 to 4 m in width with an average slope of 0.011 m/m. Banks are sandy loams stabilized by vegetative cover and tree roots. The channel bed was described as roughly 45% pool and 55% riffle by Moring (1975b). Composition of the channel bed averages roughly 20% gravel and 80% sand. Riffles are characterized by an armor layer comprised of 1-5 cm gravels overlaying a sand-gravel mixture. A channel stability evaluation after Pfankuch (1975) was performed by Paustain

(1978); Flynn Creek is rated in the fair to good category. Pools generally occur at meander bends and downstream from log steps. Riffles are interspaced between pools. A detailed longitudinal profile of the study reach is illustrated in Figure 7.

The mean daily discharge for Flynn Creek is 0.0051 m^3/s. Mean annual flood based on 18 years of record is approximately 1.5 m^3/s (Edwards, 1980). Adams (1980) presented a detailed analysis of the composition of bed materials in the study reach. His data indicate significant spatial and temporal variability in substrate composition. An analysis of 57 frozen core samples from Flynn Creek indicated an average of 22.1% by weight of inorganic material less than 1 mm diameter. Sediment transport data at the vortex sediment trap for the 1976-1979 period are summarized by O'Leary (1980) and Edwards (1980).

Huntington Creek is a third-order drainage in a region of interbedded sandstones and shales on the eastern slope of the Wasatch Plateau in central Utah. The study reach extends roughly six km downstream from Electric Lake, a 36.99 x $10^6 m^3$ water supply reservoir operated by the Utah Power and Light Company. The channel in this reach averages nine m in width with an average gradient of 0.015 m/m. A number of large beaver dams serve to catch sediments and control the location of many channel features. Pools commonly occur at river bends and riffles occur at the cross-overs between bends. The streambed is comprised primarily of small cobbles, gravels and sands. Streambanks are gravelly loams vegetated by grasses and woody shrubs.

The present hydrology of Huntington Creek is controlled almost

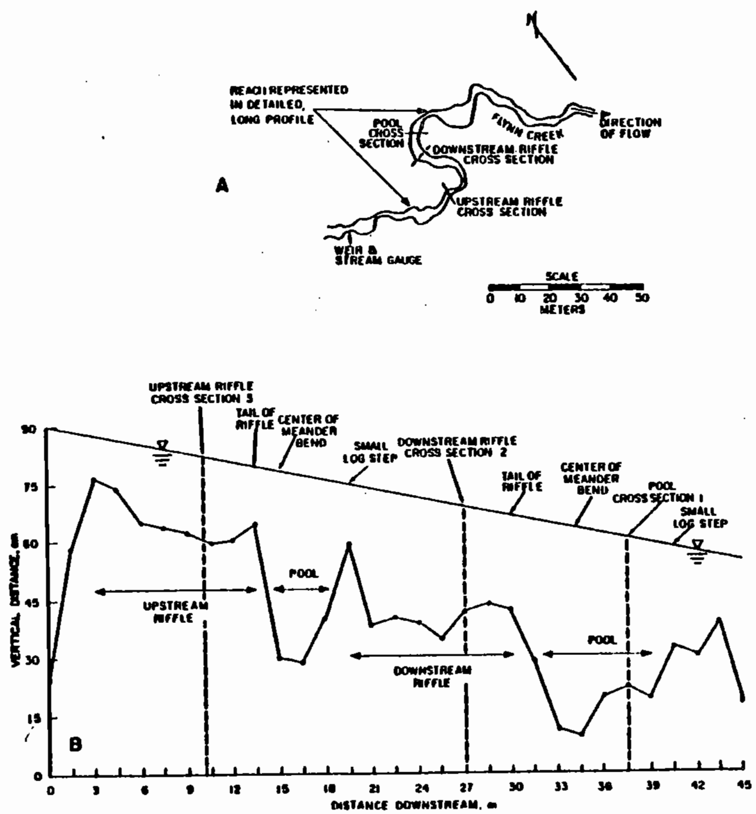


FIGURE 7. Flynn Creek study reach shown (A) in plan view as surveyed March, 1979, and (B) in longitudinal profile as surveyed January, 1980.

exclusively by the release of water from Electric Lake reservoir, completed in 1973. Seasonal peak flows have essentially been eliminated. Summer flows presently average roughly 0.40 m^3/s and bankfull flows are approximately 5.0 m^3/s in the study reach.

The 1979 release of water for the purpose of flushing fine sediments was the second such release in the past two years. In July, 1978, roughly a 5 m^3/s peak was created for the same purpose.

Methods

The field sampling program involved (1) the selection of sample locations, (2) the construction and installation of sampling bridges, and (3) the installation of fixed references for cross section measurements. Prior to and following the highest peak flow events, a series of frozen cores was obtained of the streambed at selected sites in order to assess the particle size composition of the streambed sediments. Frozen cores were obtained by the CO_2 method described by Wolkotten (1976). Core samples were dried at 100° C and weighed. The cores were then burned at approximately 300° C and reweighed to determine the approximate organic material content. Samples were then sieved to determine the particle size distribution by weight. The depth to which the streambed was sampled corresponded to the depth of maximum scour during the high flow event. The cores therefore represented freshly deposited streambed sediments at the study cross sections.

During high streamflow events the following measurements were obtained:

1. Bed elevations at 20-30 cm intervals across the channel at all cross sections.
2. Bedload transport samples at the riffles using a bedload sampler (Helley and Smith, 1971) with an enlarged bag.
3. Water surface elevation using staff gauge readings.
4. Cross section velocity profiles at 0.6 depth at riffle cross sections using either a Price current meter or a Marsh-McBirney electromagnetic velocity meter. Vertical velocity profiles were taken in the pools at the location of most rapid flow.

The 0.2 mm mesh catch bag of the Helley-Smith bedload sampler was increased to 6000 cm^2 of surface area. The large sample bag helped eliminate problems of orifice back pressures caused by a clogging of sample bag pores. Samples were composites of from 5 to 8 subsamples. Samples were frequently replicated to assist in identifying the magnitude of sampling variability. Subsample times ranged from 5 seconds to one minute, depending upon the volume rate of bedload sediment in transport. Additional samples at the middle 40 percent of the channel were obtained to further identify the variation in bedload transport rates and composition across the channel. Bedload samples were analyzed in the same manner as the frozen core samples. Particles finer than 0.2 mm were eliminated from the particle size analysis.

Sample Locations

Sample locations were selected to represent pool and riffle features which occurred in association with stream meandering rather than features induced by debris or rock obstacles. Pool cross sections were located at the deepest point of the pool. Riffle cross sections were located on the downstream third of the riffle. At Flynn Creek, one pool and one riffle (cross sections 1 and 2, respectively; Figs. 7 and 8) were monitored during the winter of 1978-1979. During the summer of 1979, an additional cross section was established at the next riffle upstream (cross section 3, Figs. 7 and 8).

At Huntington Creek, one pool and one riffle (cross sections 4 and 5, respectively) were monitored at a meander bend 6.7 km downstream from Electric Lake. A second riffle cross section (number 6) was located at a second riffle 1.4 km downstream from Electric Lake (Fig. 9).

Phase One and Phase Two Transport

During the winters of 1978-1979 and 1979-1980, only one streamflow event occurred which was of sufficient magnitude to initiate both Phase I and Phase II bedload transport with the accompanying occurrence of riffle scour and fill. On February 6-7, 1979, 6 cm of rain fell in 12 hours on the Flynn Creek watershed. A discharge peak of 1.53 m^3/s occurred at 6:00 a.m., February 8 (Fig. 10). That flow corresponded to a 1.8-year return flow (Edwards, 1980). The creek overflowed its channel prior to the discharge peak.

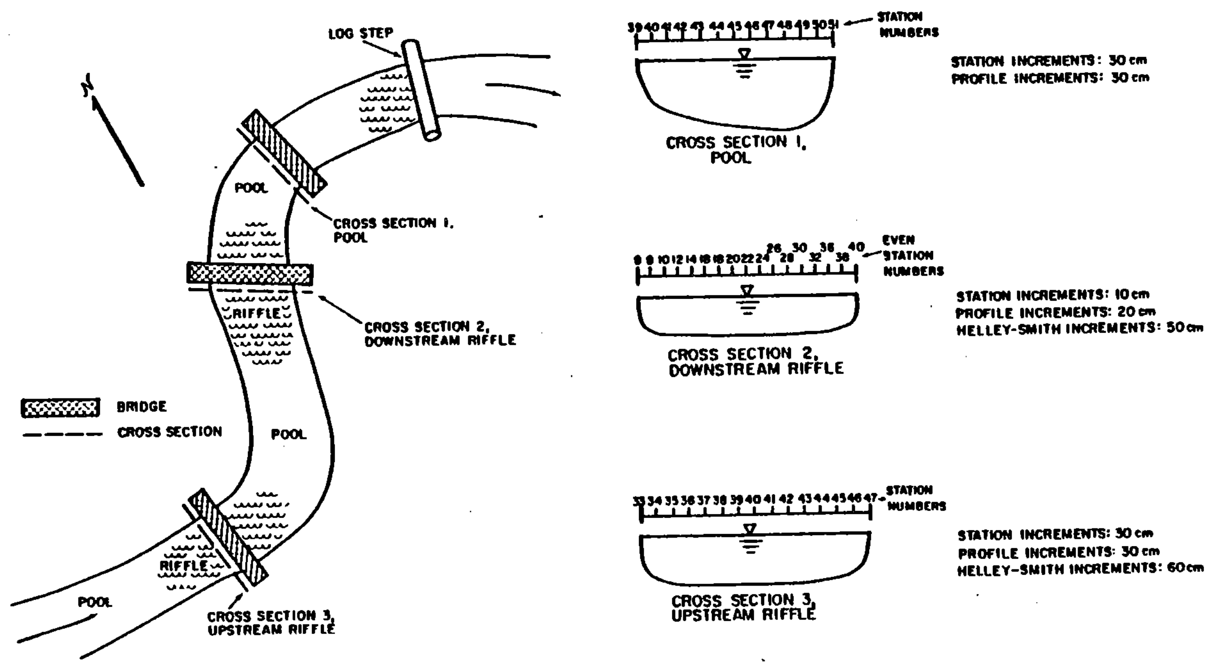


FIGURE 8. Schematic of Flynn Creek study reach showing location of sampling bridges, fixed cross sections, and cross section sampling station locations.

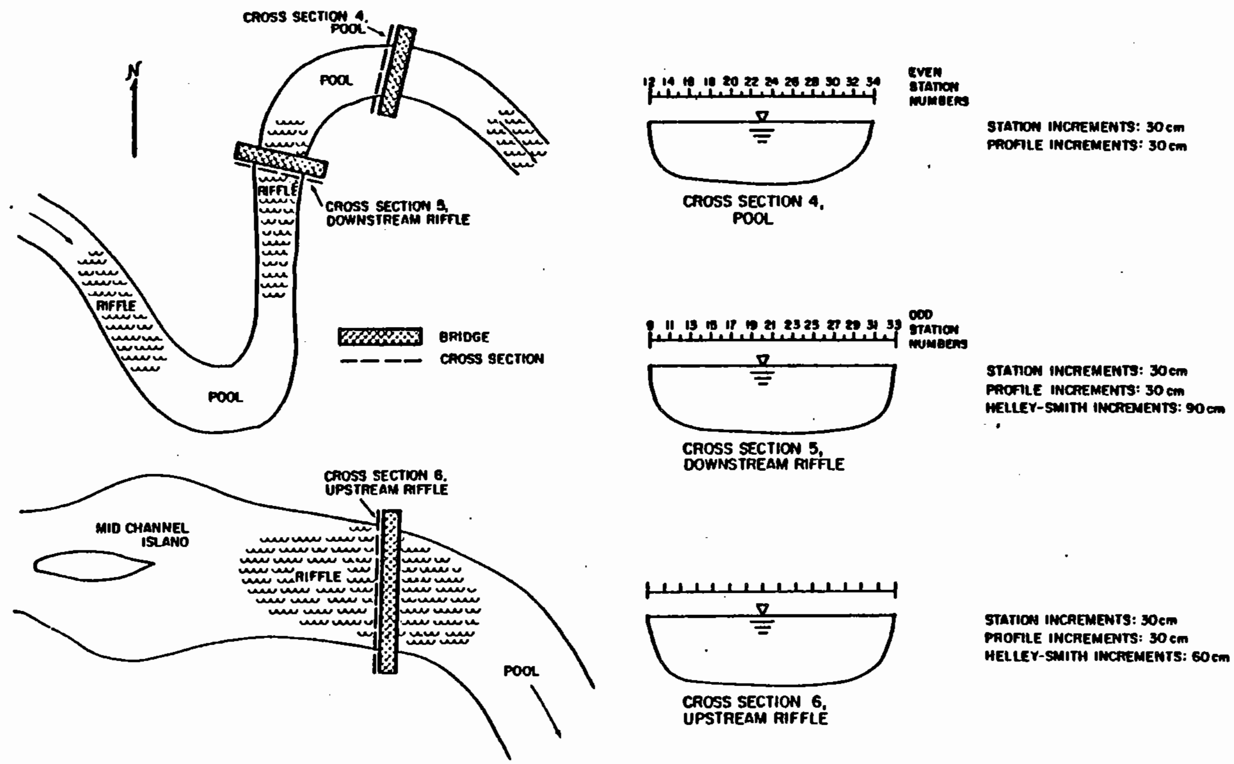


FIGURE 9. Schematic of Huntington Creek study reaches showing location of sampling bridges, fixed cross sections, and cross section sampling station locations.

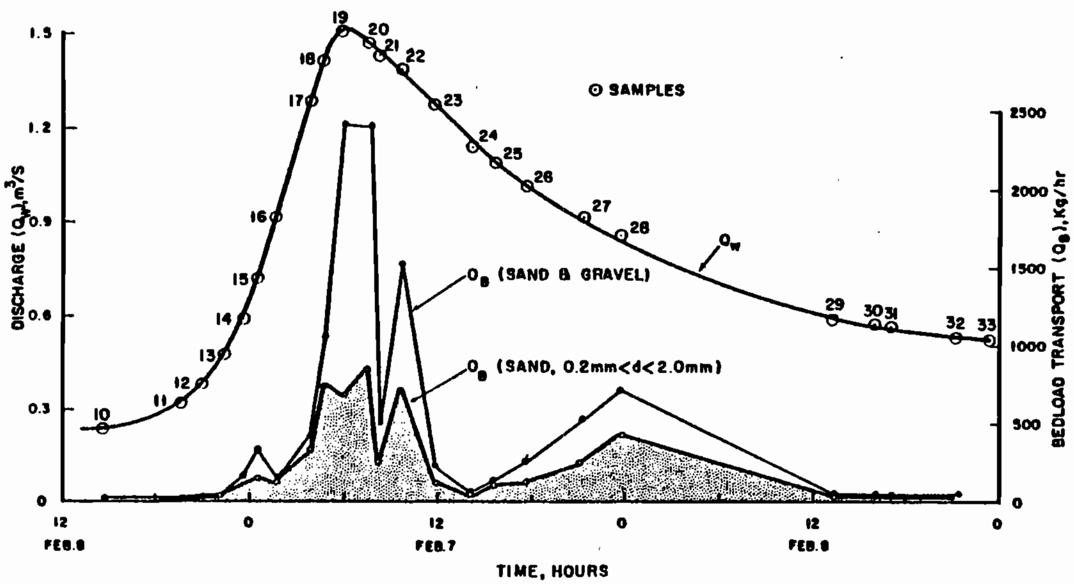


FIGURE 10. Hydrograph and bedload sediment trnasport, Flynn Creek, February 6-9, 1979.

As streamflows increased from 0.28 m^3/s to 1.35 m^3/s, bedload transport increased from zero to approximately 400 kg/hr (Fig. 10). The final 12% increase in streamflow from 1.35 to 1.53 m^3/s resulted in an increase in bedload transport from 400 kg/hr to 2400 kg/hr. This sharp increase in bedload transport was accompanied by an average scour of 20 cm at the riffle thalweg (Fig. 11).

Bedload transport rates remained closely correlated with riffle activity. In a one-hour period following the peak streamflow, bedload transport rates decreased from 2400 kg/hr to 500 kg/hr. During this same period, the main channel at the riffle underwent aggredation. Immediately following the period of streambed aggredation a second, smaller, episode of scour and fill commenced at the riffle cross section. Bedload transport rates increased from about 500 kg/hr to 1500 kg/hr during the second scour episode and then decreased to slightly over 200 kg/hr.

In this study the disturbance of the riffle armor layer and the initiation of riffle scour is defined as corresponding to the beginning of Phase II bedload transport. A dramatic local increase in bedload transport occurred at the onset of Phase II bedload transport. The increase in bedload transport was accompanied by a marked change in the composition of the sediment in transport (Fig. 12). The transport of the largest bed sediments (mean diameter greater than 12.7 mm) increased roughly 12 times and 10 times respectively during periods of riffle scour (Fig. 13).

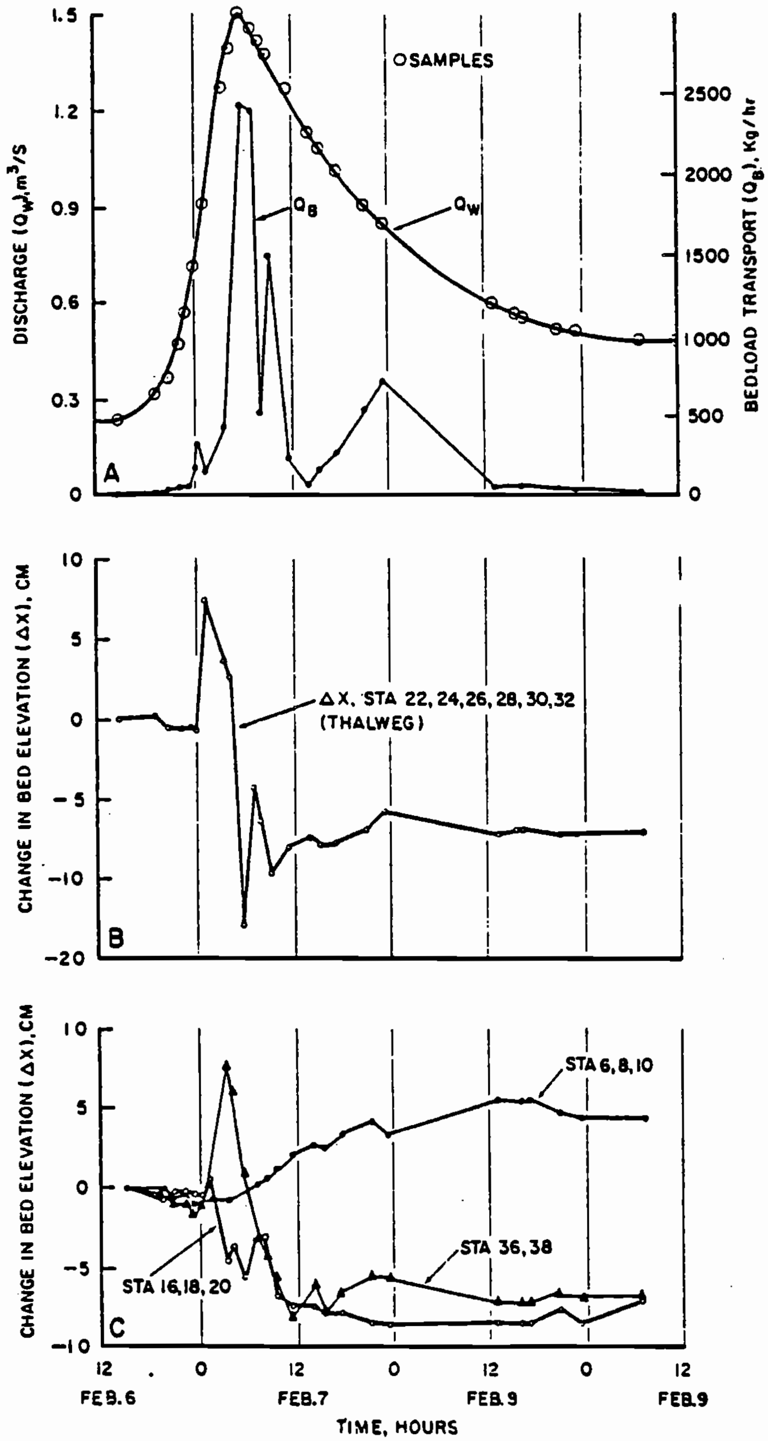


FIGURE 11. Flynn Creek (A) Hydrograph for February 6-9, 1979, and bed-load transport; (B) Average change in bed elevation for thalweg stations 22 through 32 at riffle cross section 2; (C) Average change in bed elevation for station 6 through 10, 16 through 20, and 36 and 38 at riffle cross section 2.

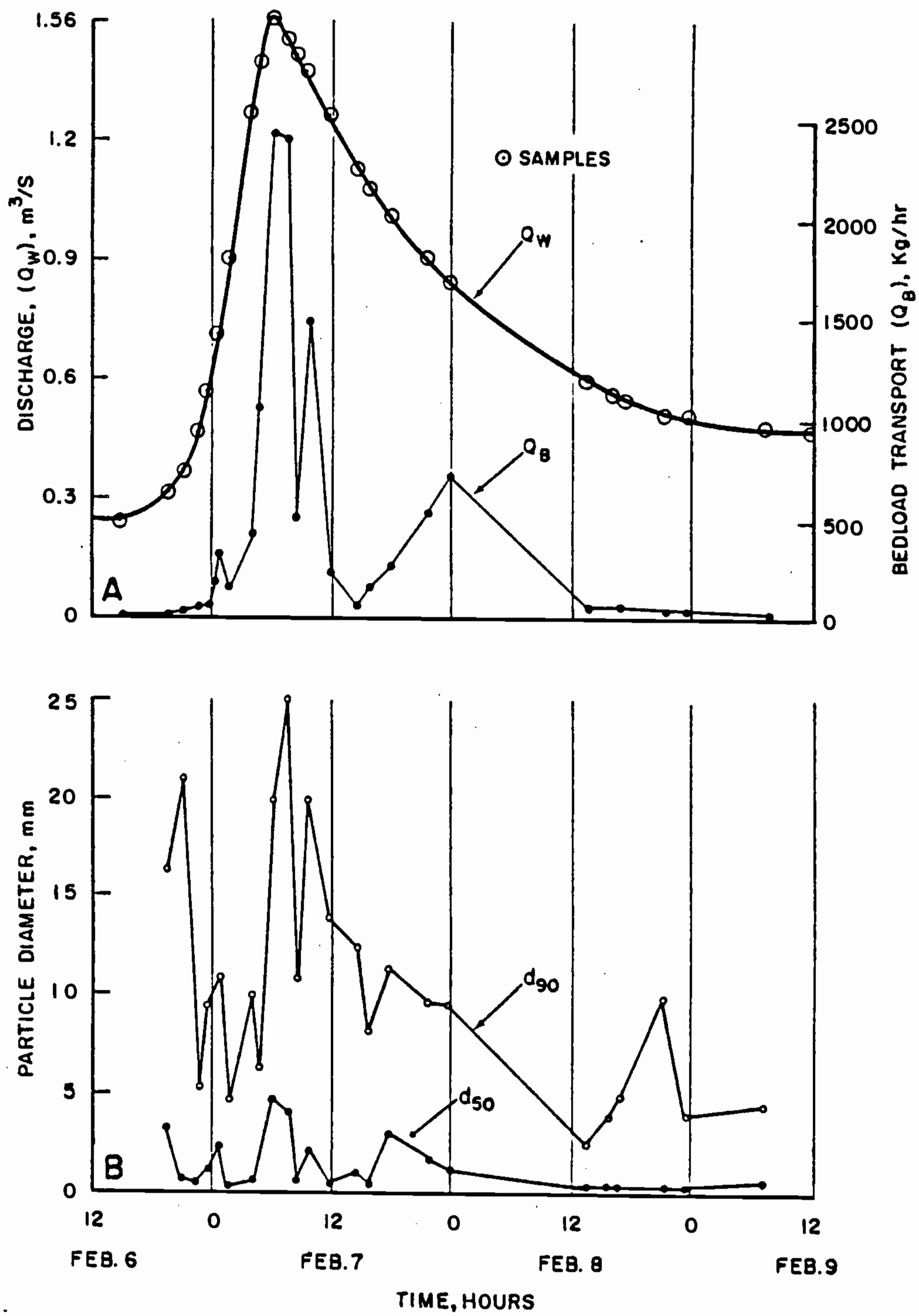


FIGURE 12. Flynn Creek (A) Hydrograph for February 6-9, 1979, and total bedload transport; (B) sediment particle diameter for which 90 percent of the bedload sediment in transport is finer (d_{90}) versus time, and particle diameter for which 50 percent of the bedload sediment in transport is finer (d_{50}) versus time.

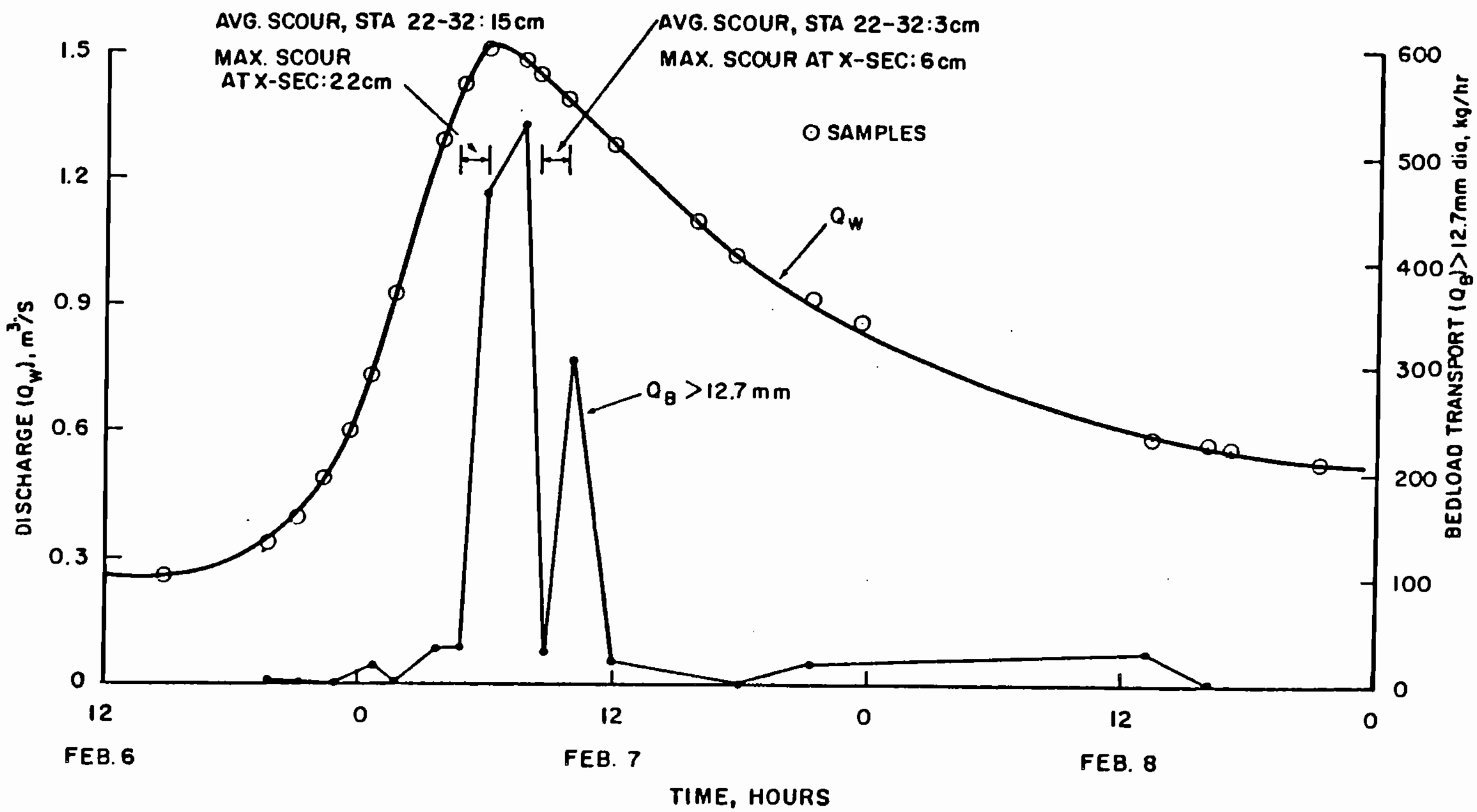


FIGURE 13. Hydrograph for February 6-9, 1979, and transport of large bedload sediment (particle diameter greater than 12.7 mm), Flynn Creek.

The water surface elevation at the riffle as recorded by the staff gauge corresponded to discharge and did not appear to be affected by streambed elevation (Fig. 14). Stage rose during increasing discharge and fell during decreasing discharge.

Following the second scour-fill cycle, the streambed in center channel had undergone a net scour of 7 cm. However, up to 13 cm of the riffle material at this location was freshly deposited. As flows receded below about 1.3 m^3/s the riffle remained essentially stable. Following the time when the riffle restabilized at the cross section, bedload transport rates increased over a ten-hour period from about 75 kg/hr to 725 kg/hr as discharge decreased from 1.27 to 0.99 m^3/s. There is not a specific explanation for the negative correlation between discharge and bedload transport during this period. Two observations suggest, however, that the transport involved Phase I bedload, or bed material not comprising newly established riffle bedforms and destined to settle out at other locations in the channel. First, there was essentially no additional scour or fill at the riffle cross section. Second, the size composition of the bed material was relatively fine. There was actually a decrease in the d_{50} and d_{90} of the transported bed material as transport rates increased, and there was little change in the transport of particles greater than 12.7 mm diameter.

Following the period of increasing bedload transport with decreasing discharge, flows continued to recede and bedload transport

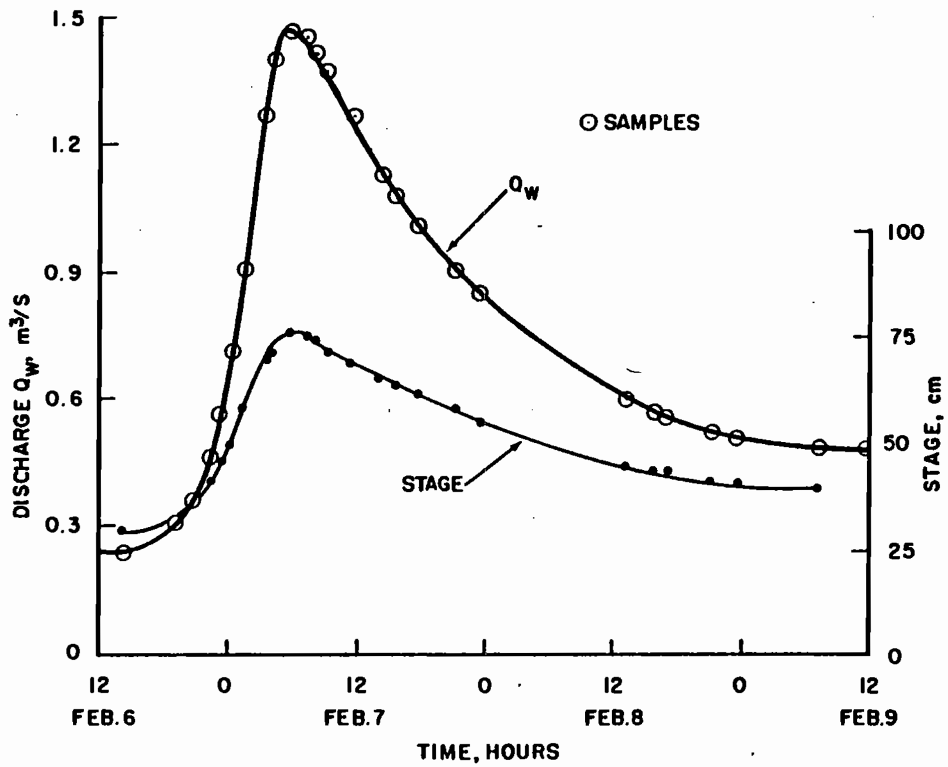


FIGURE 14. Hydrograph for February 6-9, 1969, and water stage at riffle cross section 2, Flynn Creek.

rates correspondingly receded. Phase I bedload transport rates during the recession limb at flows below 0.7 m^3/s were much less than the transport rates at corresponding flows on the rising limb. This apparent hysteresis in Phase I transport is further examined in the section on Phase I transport.

The changes in bed elevation at the riffle thalweg during the February 6-9 runoff were not representative of the behavior of the bed either at the channel edges at the riffle cross section or at the pool cross section. The far right edge (stations 36 and 38--facing upstream) of the channel at the riffle cross section underwent relatively steady scour during high flows of both rising and falling limbs of the hydrograph. The far left edge (stations 6, 8, and 10) underwent steady fill (about 5 cm) during the recession limb (Fig. 11).

The pool generally experienced a large amount of filling early in the rising limb and prior to the scour of the riffle. Stations 47-48 (thalweg) scoured prior to the peak and filled again during the recession limb of the hydrograph (Fig. 15). Stations 49-50 filled prior to the peak and then scoured on the recession limb; stations 43-46 filled both prior to and following the peak discharge. In net, the pool filled prior to the scour of the riffle and then remained essentially unchanged. Pool elevations did not correlate with bedload transport rates or scour or fill of the riffle immediately upstream. Scour and fill at two active thalweg stations--

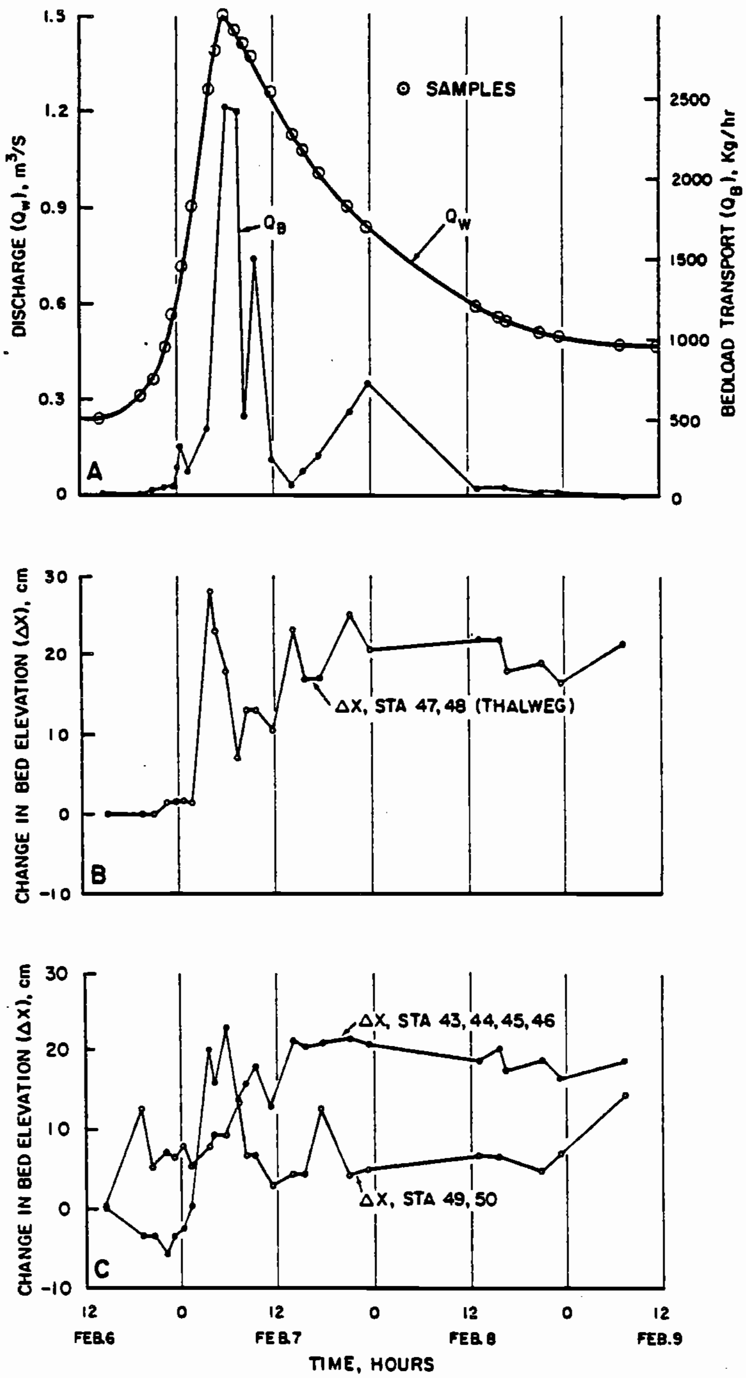


FIGURE 15. Flynn Creek (A) Hydrograph for February 6-9, 1979, and bedload transport; (B) Average change in bed elevation for thalweg stations 47 and 48 at pool cross section 1; (C) Average change in bed elevation for stations 33 through 36, and 49 and 50 at pool cross section 1.

station 32 at the riffle and station 46 at the pool--are contrasted in Figure 16. Scour-fill data for other individual stations are in Appendix I.

Several sets of Helley-Smith sub-samples were taken at thalweg stations 20 and 25 at the riffle cross section to determine the cross-section variation in bedload transport. The data indicate that bed-load transport is non-uniform across the channel and that, at higher flows, proportionately more material is transported in the center 40% of the channel (Fig. 17). A particle size analysis of the bedload material indicates that center channel transport was coarser than the total bedload transport when large proportions (> 40%) of the total transport occurred outside the center channel.

The non-uniform nature of bedload transport across the channel is probably best explained by examining the average (0.6 depth) horizontal velocity profiles of the flow (Figs. 18 and 19). As discharge increases, stream velocities increase most rapidly in the thalweg and show only minor increase, if any, along the channel edges. Average pool velocities at 0.6 depth increase somewhat more uniformly across the channel as discharge increases.

One aspect of the distribution of velocities in the pools is shown by examining the change in the vertical velocity profile at station 47 (Fig. 20) in relation to the discharge hydrograph (Fig. 10). As discharge increases, both the average and the maximum velocity in the vertical profile increase. However, the location of the maximum velocity changes dramatically near the hydrograph

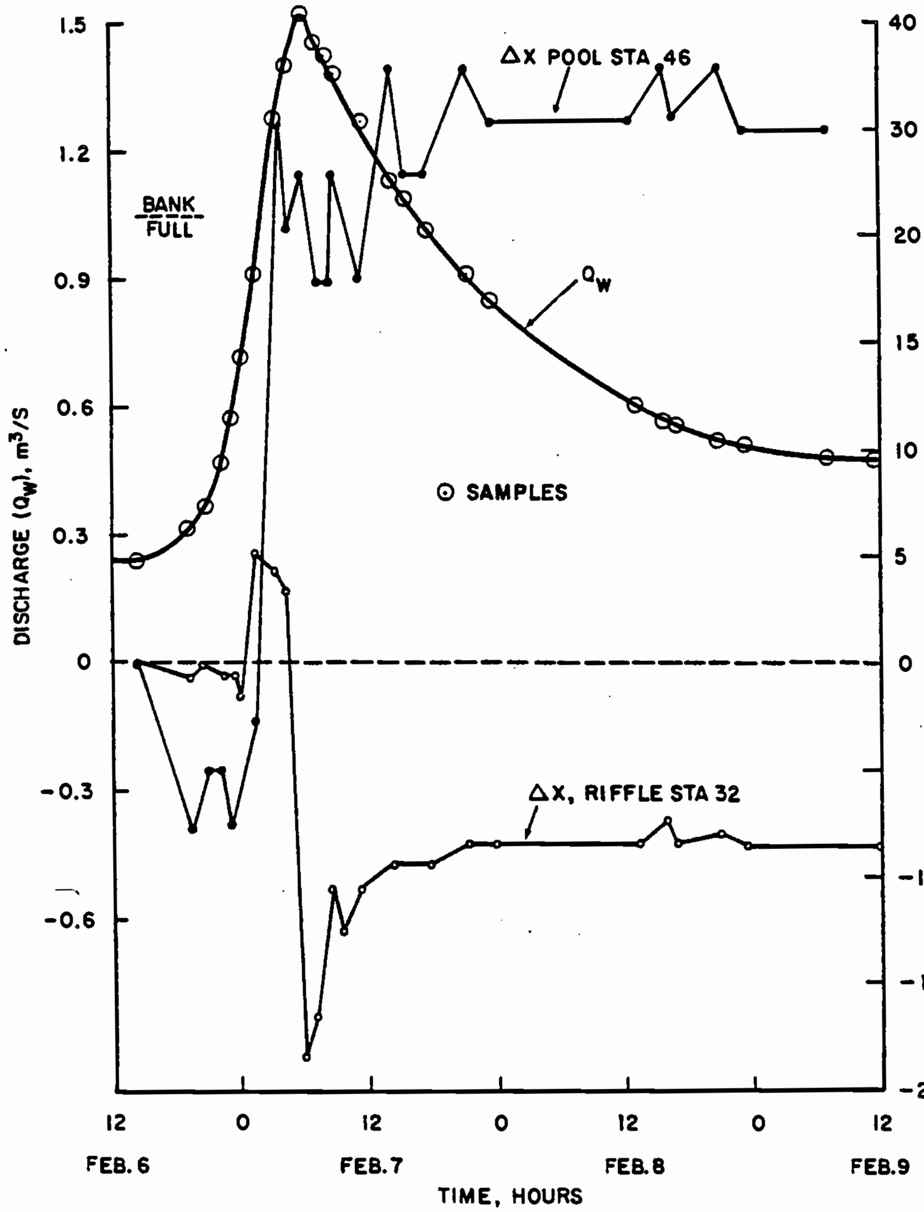


FIGURE 16. Hydrograph for February 6-9, 1979, and change in bed elevation for thalweg station 46 at pool cross section 1, and for thalweg station 32 at riffle cross section 2, Flynn Creek.

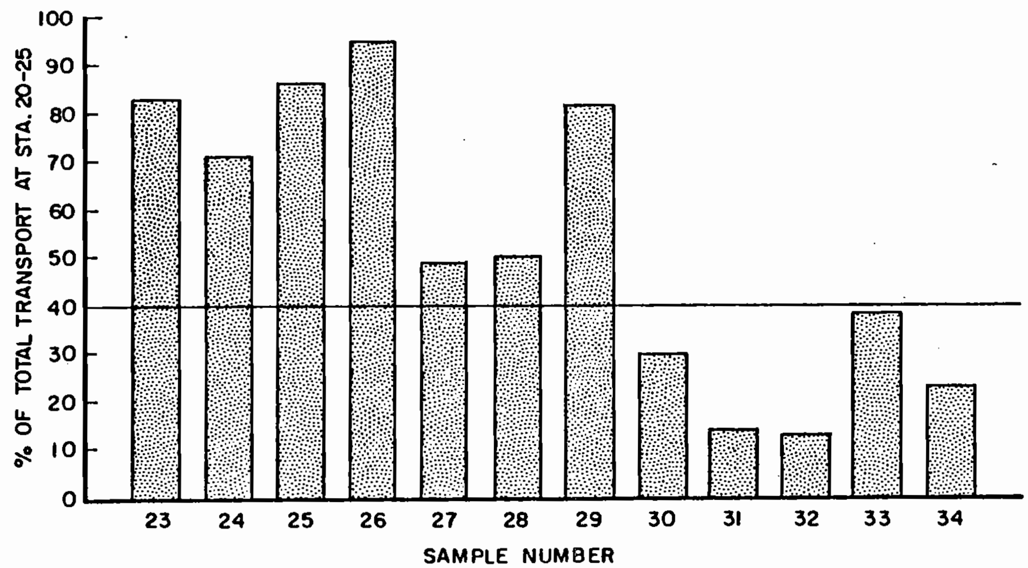


FIGURE 17. Percent of total bedload sediment transport which occurred at thalweg stations 20 and 25 at riffle 2 at Flynn Creek during the recession of streamflow, February 7-9, 1979. (Forty percent represents the percentage which would be transported at stations 20 and 25 under conditions of uniform across-channel transport rates.)

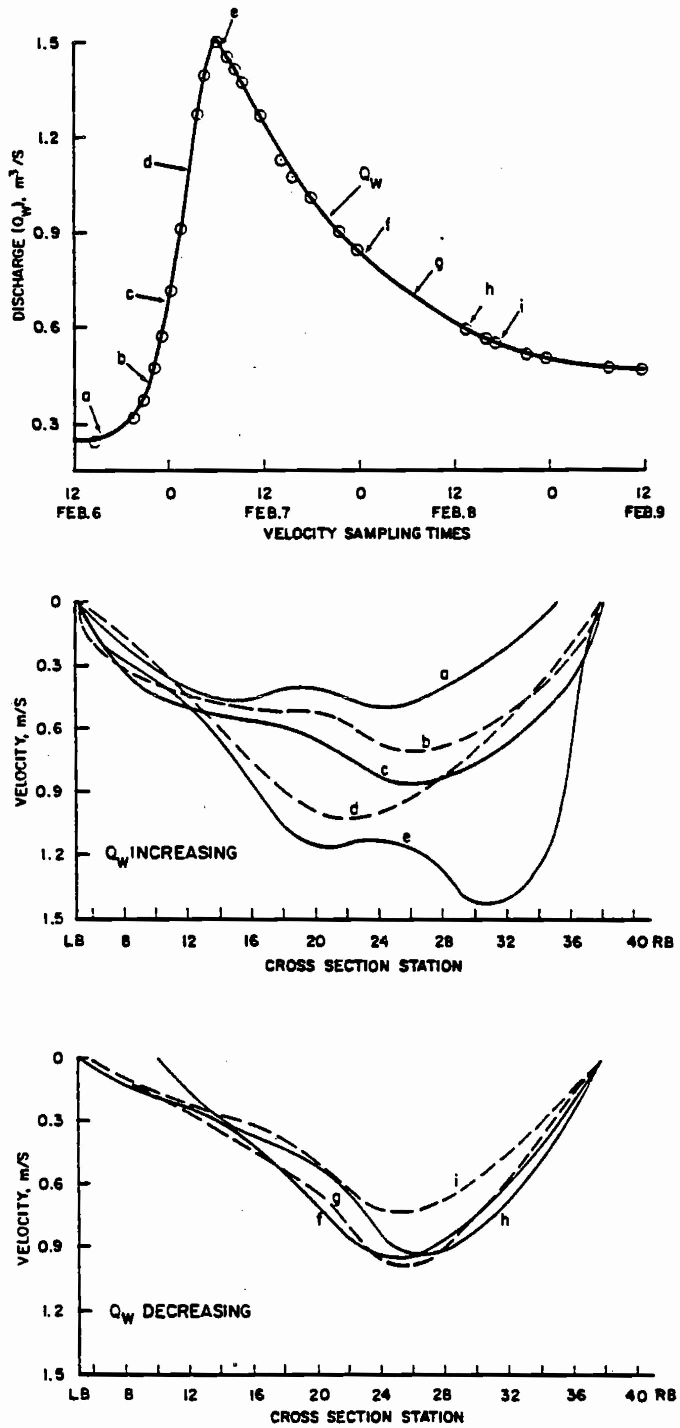


FIGURE 18. Horizontal Velocity profiles at Flynn Creek riffle cross section 2, February 6-9, 1979: (A) Velocity sampling times; (B) Horizontal velocity profiles during increasing discharge; (C) Horizontal velocity profiles during decreasing discharge.

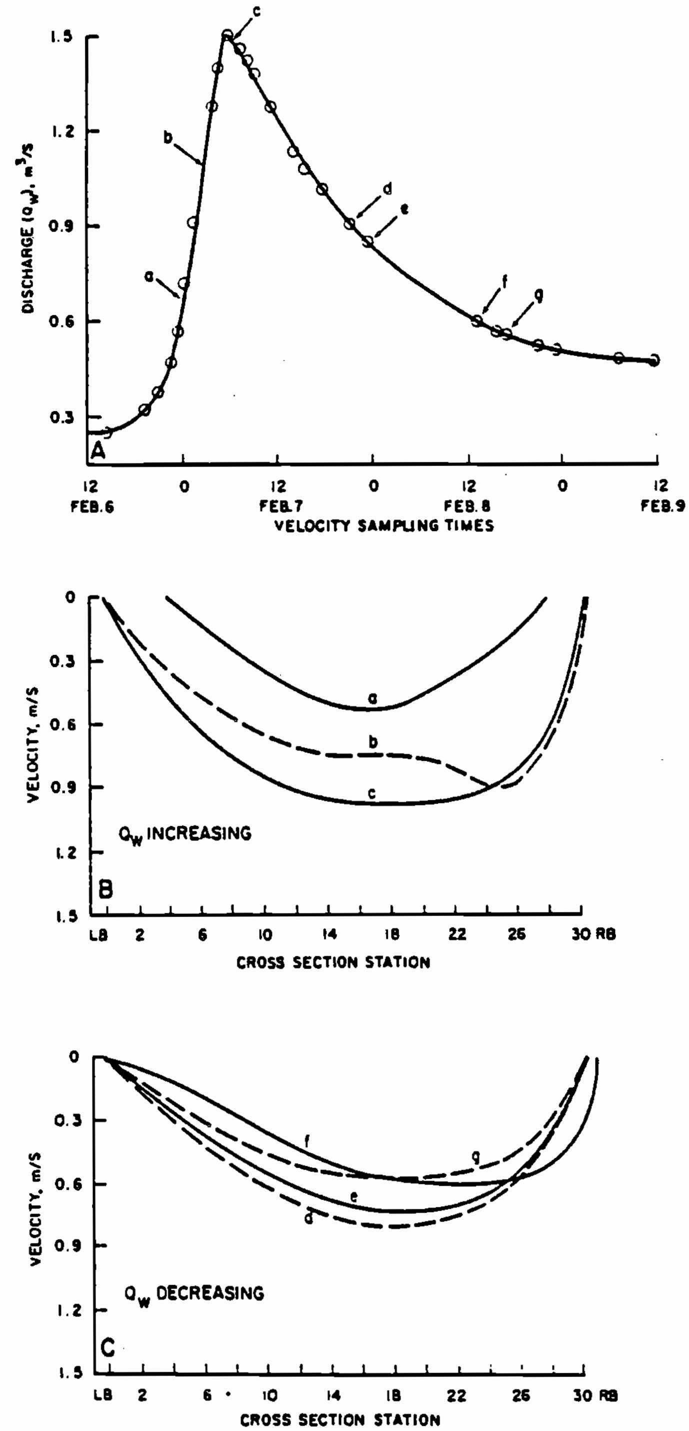


FIGURE 19. Horizontal Velocity profiles at Flynn Creek pool cross section 1, February 6-9, 1979: (A) Velocity sampling times; (B) Horizontal velocity profiles during increasing discharge; (C) Horizontal velocity profiles during decreasing discharge.

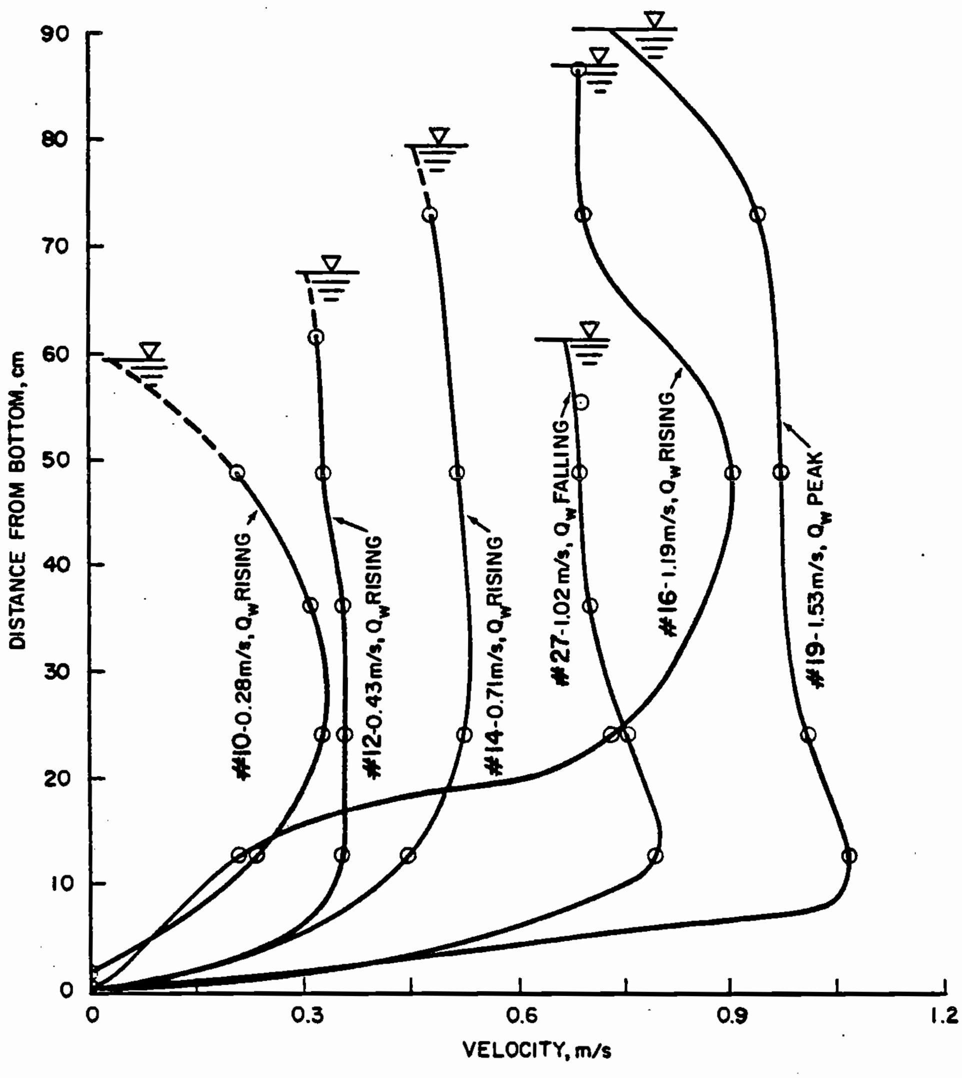


FIGURE 20. Vertical Velocity profiles at Flynn Creek pool cross section 1 at station 47, February 6-9, 1979. Profile numbers 10,12,14 and 16 on rising limb of discharge (Q_W) hydrograph. Profile number 19 at hydrograph peak; profile number 27 on falling limb of hydrograph.

peak. The maximum velocity normally occurred at mid-depth in the flow as discharges increased from about 0.28 to 1.19 m^3/s. However, at the peak discharge (1.53 m^3/s) it occurred within 10-12 cm of the bed and remained near the bottom as discharge receded to at least 1.02 m^3/s. The sharp change in the vertical velocity profile and accompanying large increase in bed shear stress near the peak in discharges did not result in a large degree of scouring of the pool, but probably did enable bed material scoured from the riffle immediately upstream to be routed efficiently through the pool.

The February 6-9, 1979, runoff at Flynn Creek resulted in up to 14 cm of freshly deposited bed material at the riffle cross section and up to 30 cm of freshly deposited bed material at the pool cross section. On February 15, 1979, five frozen cores of the fresh bed material were obtained to compare the particle size composition of the bed material to that of the bedload sediment in transport during the precise time of the deposition of the riffle material (Fig. 21). The particle size analysis shows that the bed material in the pool is finer than that in the riffle but that both are coarser than the bed material transported during deposition.

Bed material in transport at the time of riffle deposition included all size particles subsequently sampled in the riffle. However, deposition efficiencies varied with respect to particle size. There is considerably more fine and mid-size material in transport than in the resulting mid-channel streambed. The riffle is more

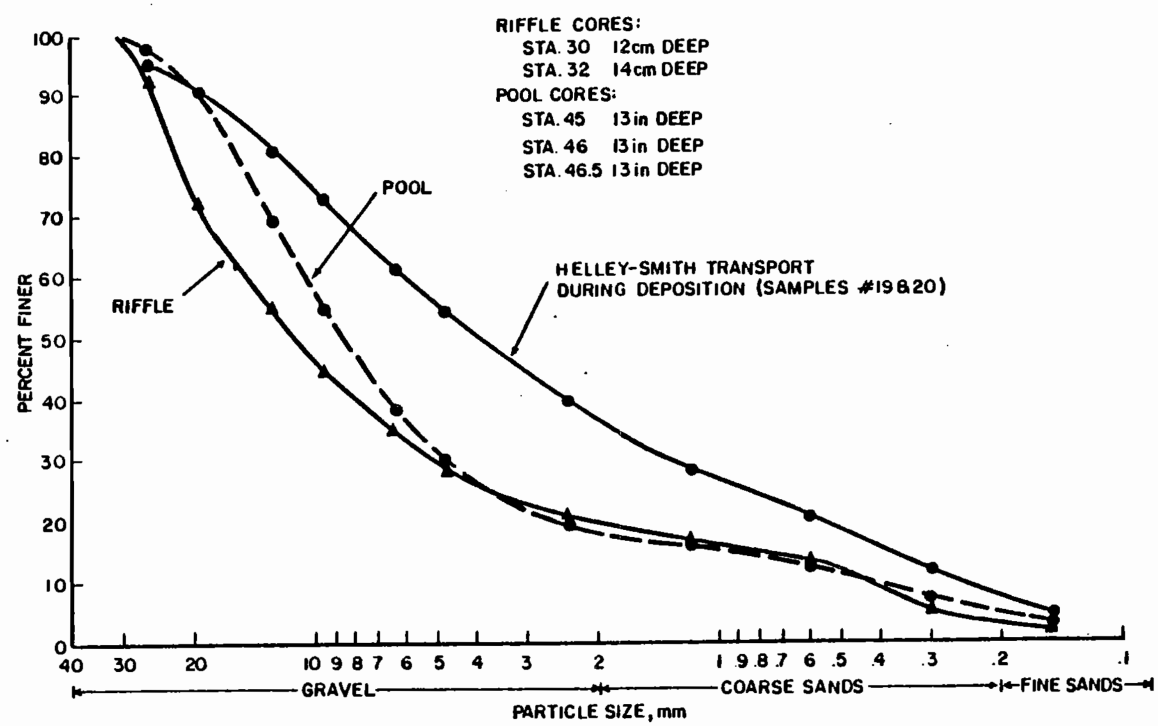


FIGURE 21. Sediment particle size analysis for bedload sediment in transport during bed deposition at riffle cross section 2, and for frozen cores of deposited bed material at pool cross section 1, and at riffle cross section 2, Flynn Creek, February 6-9, 1979.

selective towards coarse material than is the pool. The implications of variations in amount and particle size composition of bed material in transport on the resultant composition of riffle features is further examined in the flume experiments in later sections of this study.

Summary and Discussion

The February 7-10 runoff at Flynn Creek provided an excellent opportunity to test the hypothesized two-phase system of bedload transport in a small alluvial stream channel. It allowed for the measurement of the sediment transport and hydraulic conditions at the time of deposition of bed material and allowed a subsequent analysis of the resultant composition of the newly deposited bed material.

Bed material transport at the cross sections involved:

1. The transport of relatively fine bed material over a stable riffle upon the initial rise in streamflow. Bedload transport rates generally increased with discharge.

2. The disruption of the riffle armor occurred as streamflow exceeded the capacity of the channel and two cycles of riffle scour and fill subsequently occurred. Bedload transport rates increased greatly during periods of riffle scour and decreased during periods of riffle deposition. The transport of large bed material increased greatly during periods of riffle scour.

3. A restabilizing of the riffle as flows receded below the

bankfull conditions and the initiation of a ten-hour period during which bedload transport rates increased as streamflow decreased. The composition of the bedload in transport during this period was relatively fine and became finer as transport rates increased.

4. The continued recession of streamflow with corresponding decreases in bedload transport. Bedload transport rates during this period were less than those at comparable flows on the rising limb of the hydrograph.

The resultant composition of the newly deposited streambed material was coarser than the material in transport during deposition at the riffle cross section, but had the same range of particle sizes. The conditions of flow, sediment transport, scour and deposition were not uniform across the channel. The measurements at Flynn Creek help demonstrate the two-phase system of bedload transport in alluvial channels. The scour-fill and bedload transport data imply that bedload transport in this reach of stream channel is non-uniform in a downstream direction and unsteady over time at any single channel cross section. The data also suggest that gravel riffles may be the bed sediment storage components most actively undergoing change in storage in response to the non-uniform condition of Phase II bedload transport.

The accuracy, particularly of the bedload transport data, cannot be confirmed and the applicability of the descriptive processes to other streams or other runoff events has not been demonstrated. While time constraints in the field sampling program prohibited rigorous replication of Helley-Smith samples, in the several situations where replication was possible, coefficients of variation as high as 50% of the mean did occur (Fig. 22). How much of this variation was sampling error and how much represented temporal changes in bedload transport is not known. However, changes in Phase II bedload transport rates over time were generally greater than any inherent random errors in sampling. Thus, the relative changes over time are representative of real trends and the description of the processes involved remains valid.

While there is some evidence that the initiation of Phase II transport represents a break point in the slope of the power relationship between bedload transport and discharge (Fig. 23), the evidence is inconclusive due to the narrow range of discharge over which Phase II bedload transport was sampled.

Phase One Transport

Streamflow events on February 9-12, 1979, December 4, 1979, and January 12-16, 1980, at Flynn Creek and the August 7-10, 1979, release at Huntington Creek resulted in the transport of bed sediments but were insufficient in magnitude to disrupt riffle armor sediments and initiate Phase II bedload transport. As a result, there was little or no measured change in streambed elevations at riffle cross sections and no change in the sediment composition of riffle features. These streamflow events, however, did provide additional opportunity

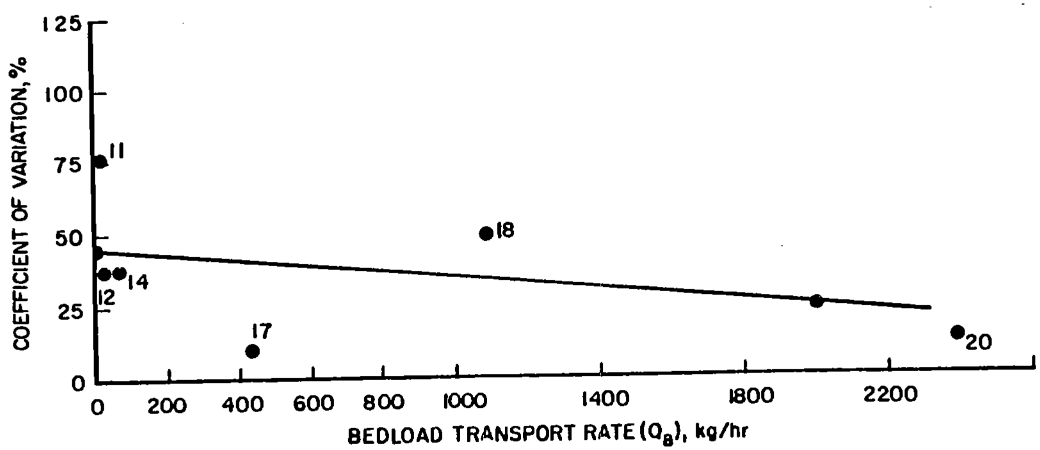


FIGURE 22. Coefficient of variation for replicated bedload transport samples (sample number shown) versus bedload transport rate; Riffle cross section 2, Flynn Creek, February 6-9, 1979.

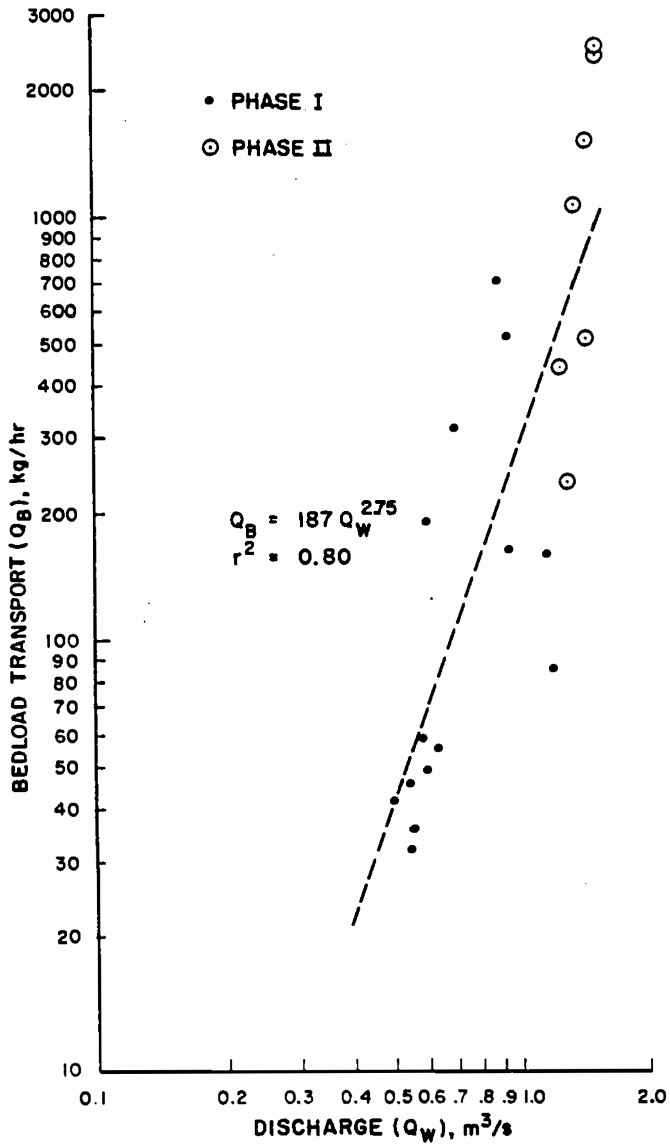


FIGURE 23. Bedload transport versus water discharge, riffle cross section 2, Flynn Creek, February 6-9, 1979.

to characterize Phase I bedload transport in alluvial streams.

Huntington Creek

A simulated storm hydrograph was generated in Huntington Creek, Utah, by the controlled release of water from Electric Lake Reservoir from August 7-10, 1979. Discharge was increased incrementally over a ten-hour period from 0.40 m^3/s to 4.90 m^3/s. The discharge peak of 4.90 m^3/s was maintained for 13 hours, after which flows were reduced to 2.75 m^3/s for three hours. A second, smaller discharge peak of 4.36 m^3/s was then maintained for 40 hours before discharge was finally reduced to 1.19 m^3/s over a five-hour period.

The increase in bedload transport correlated strongly (r^2 = 0.92 upstream, r^2 = 0.99 downstream) with the increase in discharge on the rising limb of the discharge hydrograph at both riffle cross sections (Figs. 24 and 25). Peak rates of bedload transport of 1652 kg/hr and 1501 kg/hr occurred at the upstream and downstream cross sections respectively at or shortly after the attainment of the discharge peak of 4.90 m /s. During the 13-hour discharge peak, bedload transport rates became erratic and variable over time. A least squares fit of the data, however, indicated significant ($p = 0.99$) negative slopes in the relationships between bedload transport and time at the two riffle cross sections (Figs. 24 and 25). It is believed that the decrease in bedload transport over time at constant discharge is the result of limitations in the in-channel availability of Phase I sediments for transport. The slope of the bedload

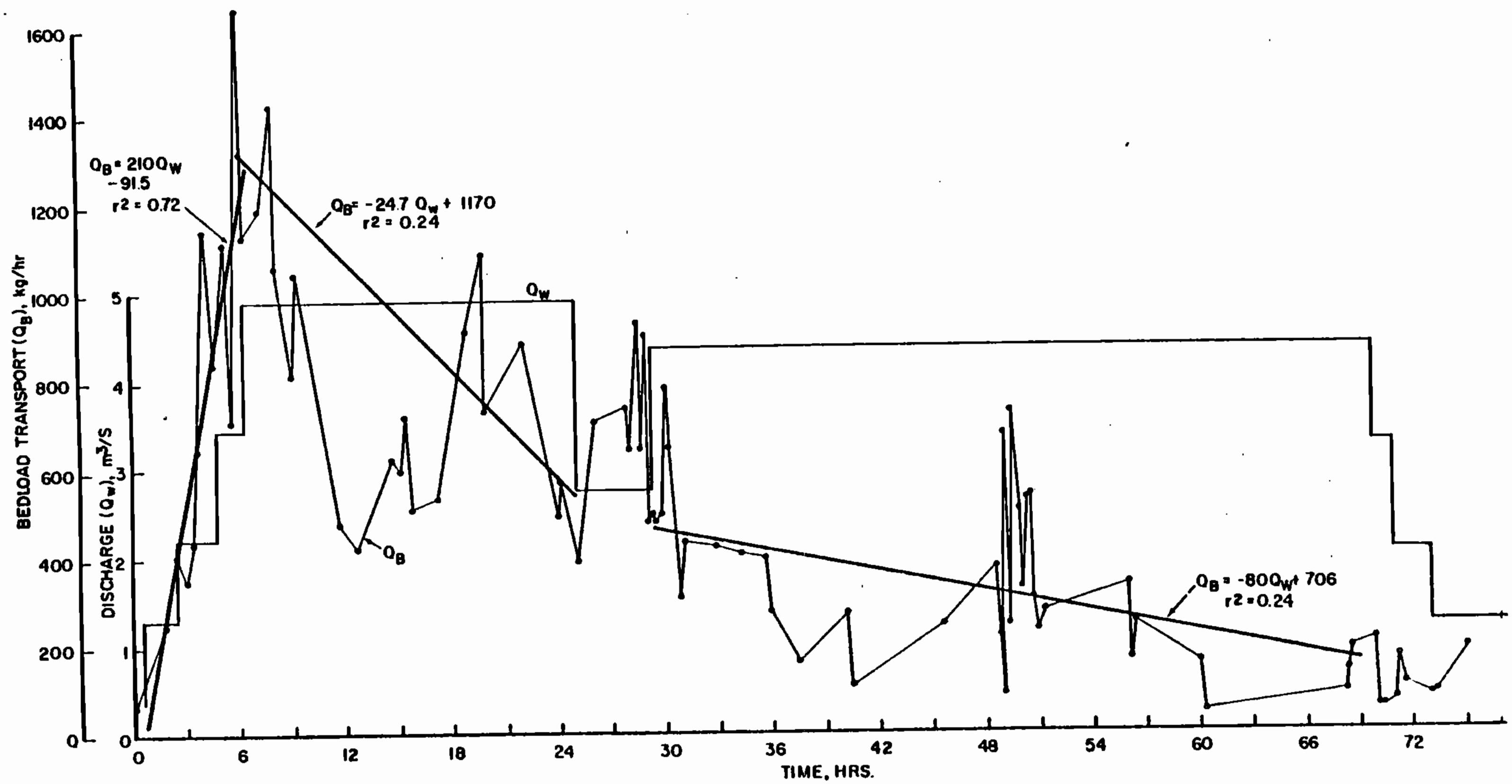


FIGURE 24. Discharge and bedload transport, riffle cross section 5 (downstream) Huntington Creek, August 7-10, 1979.

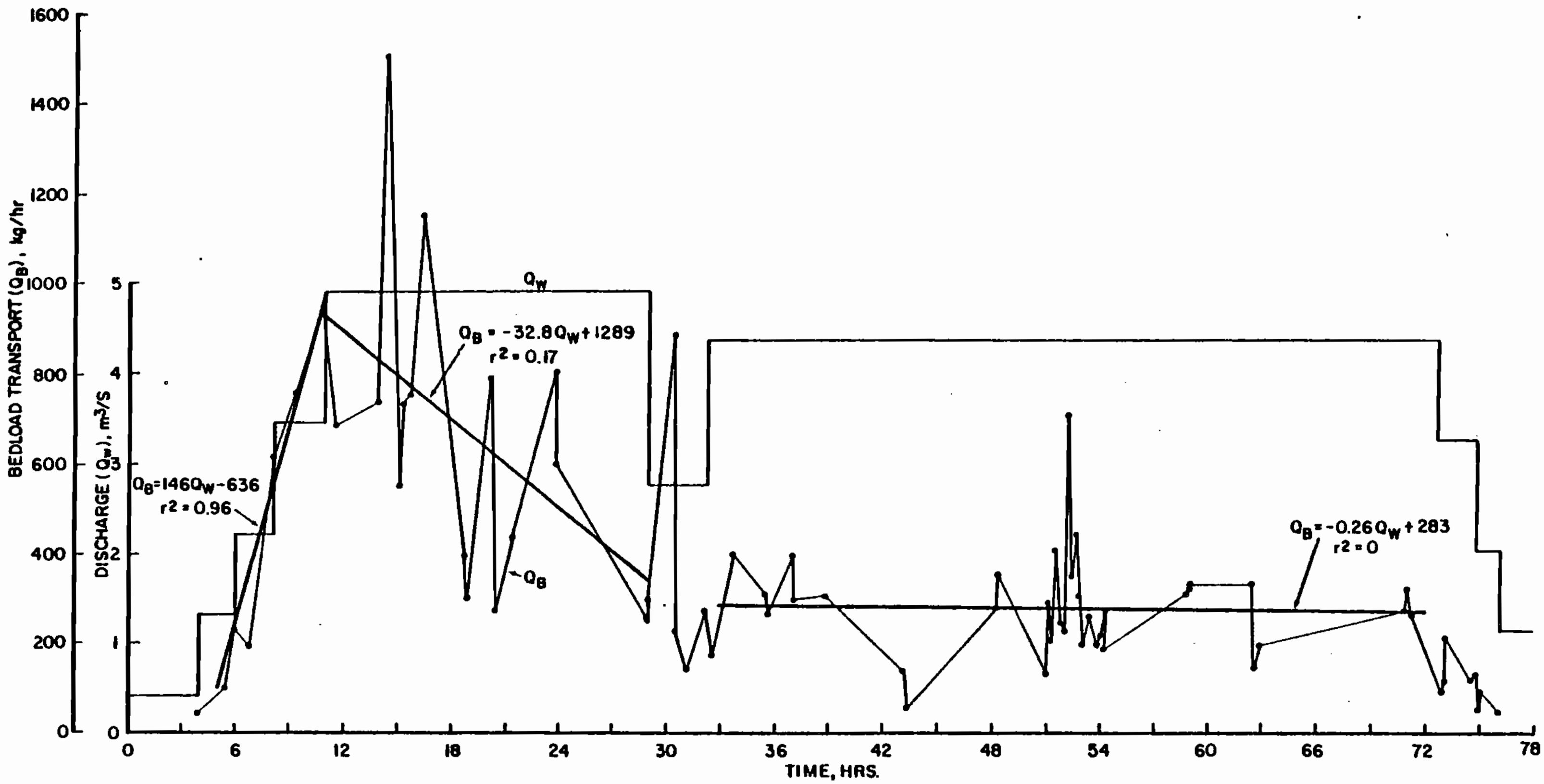


FIGURE 25. Discharge and bedload transport, riffle cross section 6 (upstream) Huntington Creek, August 7-10, 1979.

transport vs. time relationship during the second, smaller discharge peak was negative at both cross sections. The negative slope, however, was not significantly different from zero ($p = 0.95$) at the downstream riffle cross section and was significant at the 95 percent level, but not at the 99 percent level at the upstream riffle cross section.

The average bedload transport rates during the second, smaller discharge peak were 344 kg/hr and 270 kg/hr at the upstream and downstream cross sections respectively. The corresponding coefficient of variation was 0.38 at the downstream cross section. Thus, the Phase I bedload transport variability over time corresponds closely with the sampling variability associated with the Helley-Smith bedload sampler as determined by replicate sampling during the February 7-10, 1979, Flynn Creek runoff. Replicate sampling from hours 49-51 (upstream) and 51-54 (downstream) at Huntington Creek indicated coefficients of variation of 0.51 and 0.48 respectively at the upstream and downstream stations. Thus, because of sampling variability, apparent variations in Phase I bedload transport at Huntington Creek were not significantly different from the mean transport rate.

A particle size analysis of the material in transport indicated no trends in median particle diameter (d_{50}) or the 95 percent size (d_{95}) over time or in relation to discharge. Median particle size and the d_{95} was larger at the upstream cross section than the downstream cross section (Table 1). The range of sizes of bed material

TABLE 1. Particle sizes of bed material in transport and riffle sediments at riffle cross sections 5 and 6, Huntington Creek, Utah

	Location	Median particle diameter, d_{50}, mm	Slope m/m	95% Article diameter, d_{95}, mm	Slope m/m	Number of Samples
Transported Bed Material	Downstream (Cross Section 5)	.37	.17	8.2	4.9	44
	Upstream (Cross Section 6)	.79	.66	14.0	3.6	55
Riffle Bed Materials	Downstream (Cross Section 5)	13.9	4.2	41.3	6.7	10
	Upstream (Cross Section 6)	2.5	2.9	27.9	11.7	10
Armor Sediments	Downstream (Cross Section 5)	25.0	-	44.0	-	1
	Upstream (Cross Section 6)	16.0	-	36.0	-	1

in transport was smaller than that of the material comprising the riffles and did not include the larger particle sizes found in the riffle cores. The particle size analysis, in addition to the cross section measurements, indicate that riffle sediments were not transported during the August 7-10, 1979, streamflow event. While the decrease in bedload transport rates over time at Huntington Creek at constant peak discharge indicates a possible supply control over Phase I bedload transport, the lack of any trends in sizes of material in transport does not suggest that supply limitations are a function of sediment particle size.

It is also interesting to note that the decrease in bedload transport over time at the constant peak discharge is no more pronounced at the upstream cross section than the downstream cross section. Since the downstream cross section is an additional 5.3 km from the dam, it might have been expected that greater supplies of in-channel sediments would be available for transport at the downstream cross section. No explanation is provided for the absence of more pronounced decreases of bedload transport over time at the upstream cross section compared to the downstream cross section. It is true, however, that the bedload transport capacity per unit width of streambed was lower at the downstream cross section due to the larger cross sectional area of flow.

Flynn Creek

Phase I bedload transport occurred at Flynn Creek during streamflow events on February 9-12, 1979, December 4, 1979, and January 12-16, 1980. Discharge peaks for the three events were 0.8 m/s, 0.65 m/s and 0.85 m/s, respectively. These discharges were insufficient to transport riffle armor sediments at either of the monitored riffle cross sections. Therefore, Phase II bedload transport, as defined, did not occur. There was some minor readjustment of the cross section profile at the downstream riffle (#2) during the February 9-12, 1979, period. Approximately 1-2 cm of scour was recorded along the channel edge (stations 16-20) and approximately 1-2 cm of deposition was recorded along the other channel edge (stations 26-38). The channel thalweg remained essentially stable.

Bedload transport was variable over time, but generally correlated positively with discharge during all three events (Figs. 26 to 28). A bedload rating curve indicates that the relationship between bedload transport and discharge, although weak ($r^2 = 0.51$), was significant ($p = 0.95$) for data from all three streamflow events (Fig. 29).

The February 10-12, 1979, event did exhibit decreased bedload transport on the falling limb of the hydrograph in comparison to similar discharges on the rising limb. It is not known if this hysteresis is the result of a supply limitation. It is interesting to note that the February 10-12, 1979, runoff immediately followed the larger February 7-10 runoff, which resulted in considerably larger volumes of bed material transport and which also exhibited a rising limb-falling limb hysteresis during Phase I transport.

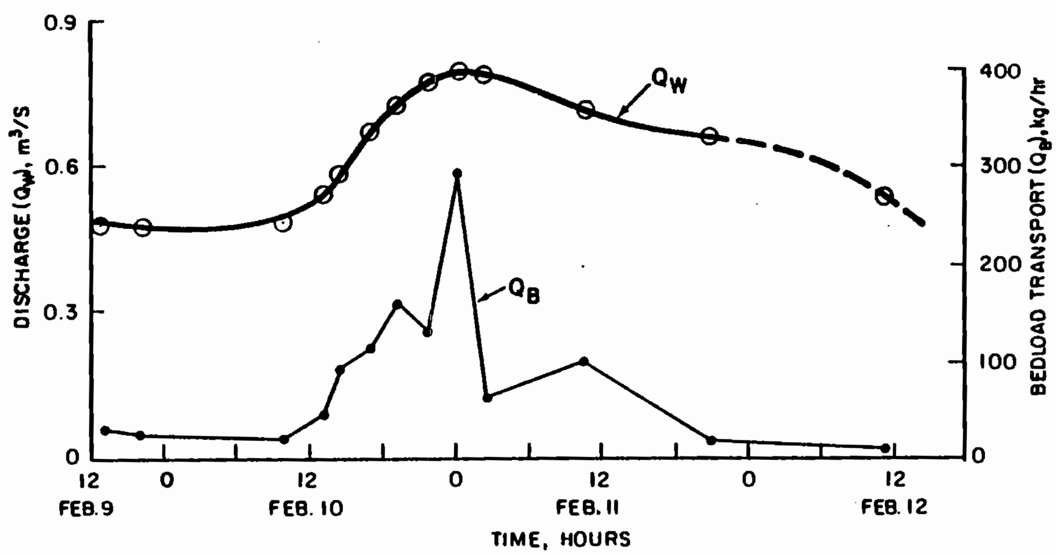


FIGURE 26. Discharge and bedload transport, riffle cross section 2, Flynn Creek, February 9-12, 1979.

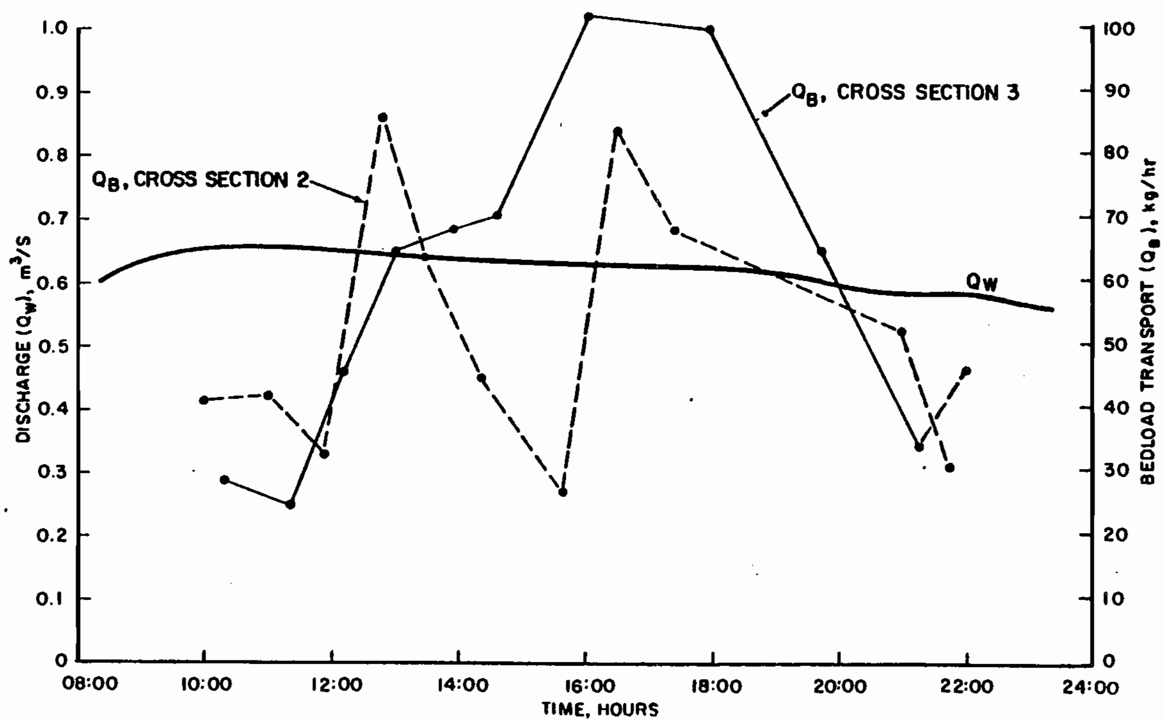


FIGURE 27. Discharge and bedload transport, riffle cross sections 2 (downstream) and 3 (upstream), Flynn Creek, December 4, 1979.

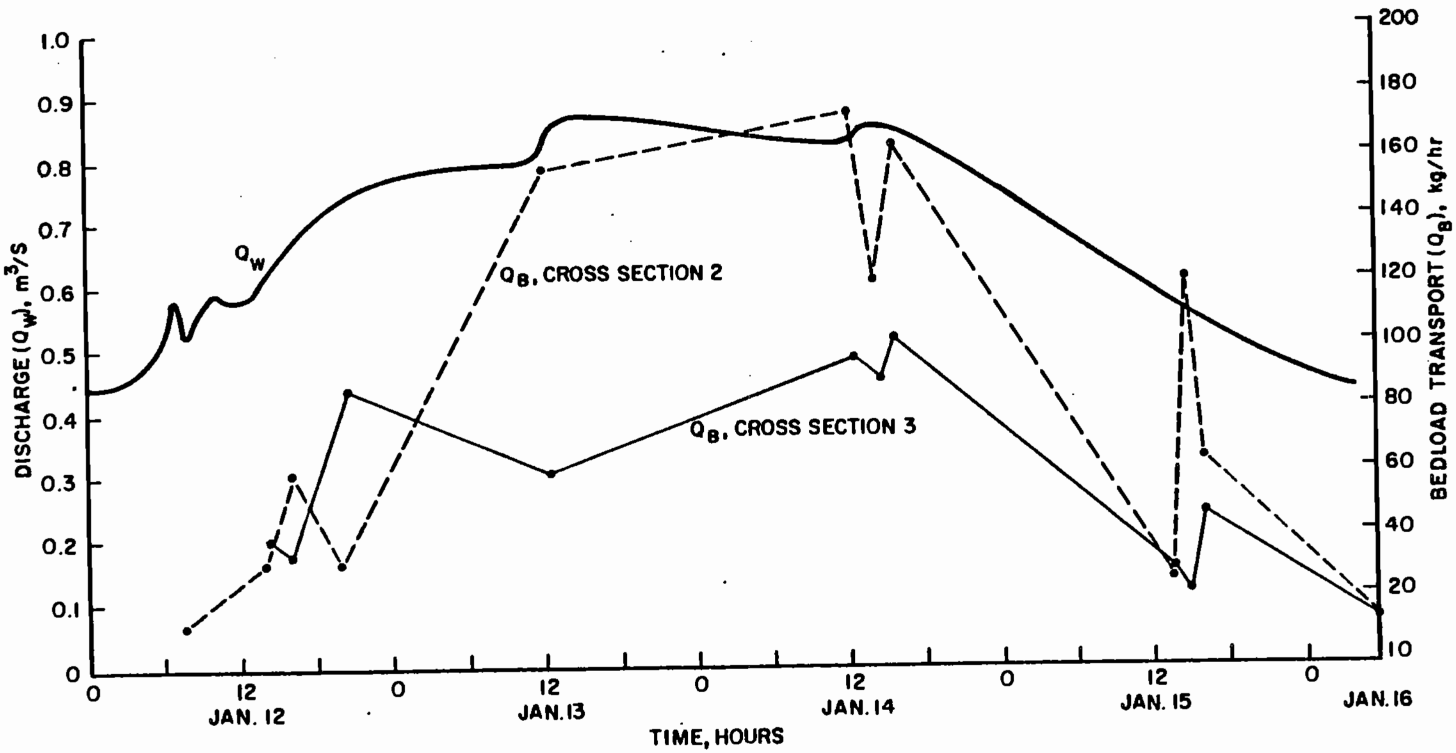


FIGURE 28. Discharge and bedload transport, riffle cross sections 2 (downstream) and 3 (upstream), Flynn Creek, January 12-16, 1980.

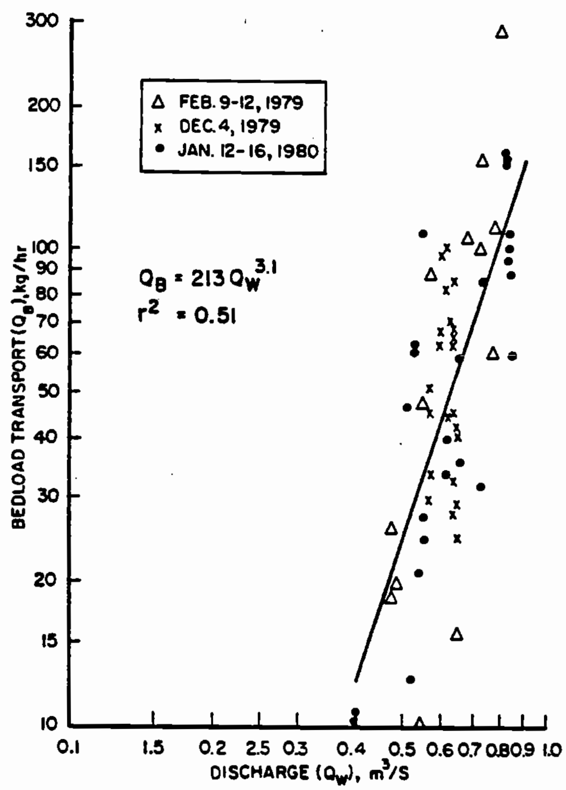


FIGURE 29. Bedload transport versus discharge for 3 small storms, Flynn Creek, Oregon.

Coefficients of variation for replicated samples during the December 4, 1979, and January 12-16, 1980, events averaged 28 and 33 percent respectively with a range of zero to 99 percent. Although there is some indication that Phase I bedload transport is an unsteady non-uniform process, the lack of sampling precision makes any unsteady characteristics of the transport process difficult to verify and characterize. In addition, measurements of channel cross sections were insufficient to detect the changes in sediment storage at a point which would be characteristic of unsteady, non-uniform bedload transport. In any case, it did not appear that riffle sediments were involved to any major extent in bedload transport during the February 9-12, 1979, December 4, 1979, or January 12-16, 1980, streamflow events.

A particle size analysis of the material in transport indicated no trends in mean particle size (d_{50}) or the 95 percent size (d_{95}) over time or in relation to discharge. Mean particle size for all three events was 0.65 mm (s = 0.31 mm). The range of sizes of bed material in transport was smaller than that of the material comprising the riffles and did not include the larger particle sizes found in the riffle cores.

IV. FLUME STUDIES

Field studies at Flynn Creek and Huntington Creek demonstrated the hypothesized two-phase system of sediment transport in alluvial channels exhibiting sequences of pools and riffles. The field studies characterize the timing of streambed scour and deposition during periods of high streamflow.

It was not feasible to rigorously examine in the field the two processes which are hypothesized to account for changes in the composition of stream gravel substrate. Phase II transport, with associated scour and deposition of riffle sediments, appears to occur on the order of once every 1-2 years. Either a long period of time or a large number of streams would need to be evaluated to clearly define the effects of sediment and hydraulic variables on the scour and deposition of bed materials. Phase I transport and the intrusion of fine sediments into stable gravel substrate occurs during periods of increased streamflow when core sampling of the streambed is not feasible. Insertion of the coring probe at these flows could affect the fine sediment composition of the gravels being sampled.

To further examine the relationship between Phase I and Phase II bedload transport and changes in the composition of streambed gravels, a series of three flume experiments was designed. The first experiment was designed to study the effects of flow and sediment size on the rate and extent of intrusion of fine sediments

(< 2 mm) into a stable streambed gravel matrix. This is a process which may occur during Phase I transport. The second experiment was designed to examine the effects of the size gradation of transported sediments and rate of transport on the composition of resultant riffle deposits. These are variables involved during the scour-fill cycles associated with Phase II transport. The third experiment was designed to test changes in the stability of riffle features associated with changes in the rate and amount of Phase I bedload transport. The purpose of this experiment was to gain insight into the relationship between Phase I bedload transport and the initiation of Phase II transport.

Intrusion Experiments

Sediment intrusion can be characterized by two competing processes. In the first process, sediment particles settle out of the flow and become trapped in the gravel pores near the surface. Sediment particles are "filtered" when they are larger than the pore spaces in the gravel streambed. A discussion of the particle size requirements for granular material in order that it effectively filter finer particles is provided in Sowers and Sowers (1970). In the second process, fine sediment particles settle out of the flow and intrude into the gravel matrix apparently filling the matrix from the bottom up. It is hypothesized that the total amount of intrusion is a function of the relative rate of deep intrusion of sediment particles compared to the rate of intrusion of filterable particles. This total intrusion results in the formation of a seal, or barrier, to further deep intrusion.

Studies by Cooper (1965) and Einstein (1968) measured the intrusion of silt-sized sediments into stable gravel beds. They found that the intrusion rate was a function of the settling velocity of the sediment particles and the concentration of the sediment in the flow. Beschta and Jackson (1979) further noted that larger sand-sized sediments may form a seal near the surface of the gravel bed and block the intrusion of finer sediments into available gravel pore spaces. In this case the extent and rate of intrusion was not only a function of settling velocity and particle size, but also the rate of seal formation.

The objectives of the intrusion experiments were to:

1. Examine the effects of varying proportions of intrudable versus filterable sediment particles in transport on the rate and extent of intrusion into a gravel substrate.

2. Examine the effects of flow conditions on the vertical distribution of sediment particles in the flow and the effects on the rates of intrusion and surface sealing.

Methods

These experiments were conducted during the summer of 1979 at the Weyerhaeuser Company Kalama Springs Field Laboratory located approximately 80 km east of Longview, Washington. A rectangular plywood flume, 7.6 m long and 35 cm wide was utilized. The first

5.8 m of length was 30 cm deep. The last 1.8 m section was 51 cm deep and served as the test reach. Fresh gravels with a median particle size of 17 mm (Fig. 30) were placed in the test reach to a depth of 21 cm for each run. The flume was hinged at the upstream end and several pairs of hydraulic jacks were spaced along the flume for support and a means of adjusting the bottom slope. A side channel and a set of gates provided a means of instantaneously stopping and starting flow into the flume. Rubber foot mats placed on the upstream 5.8 m of the flume simulated the hydraulic roughness of the gravel bed in the test reach. A 31 cm wide Scott fertilizer spreader and hopper were mounted on top of the flume at its upstream end. The spreader was powered by an electric motor and sediment input rates to the flume were controlled by setting the size of the spreader apertures.

For each experimental run, sands were added to the flow at a rate of approximately 157 kg/hr. The particle size gradation of the sands was controlled by pre-mixing a standard coarse sand and a standard fine sand (Table 2).

Three finely perforated cans 18 cm high by 10.8 cm diameter were buried in the gravel test reach prior to each run. After each run they were extracted and served as subsamples of the gravels with intruded sands. Samples retrieved from the buried cans were dried at 100° C and then analyzed for (1) percent intruded sand, by weight, and (2) size gradation of intruded sand. The size

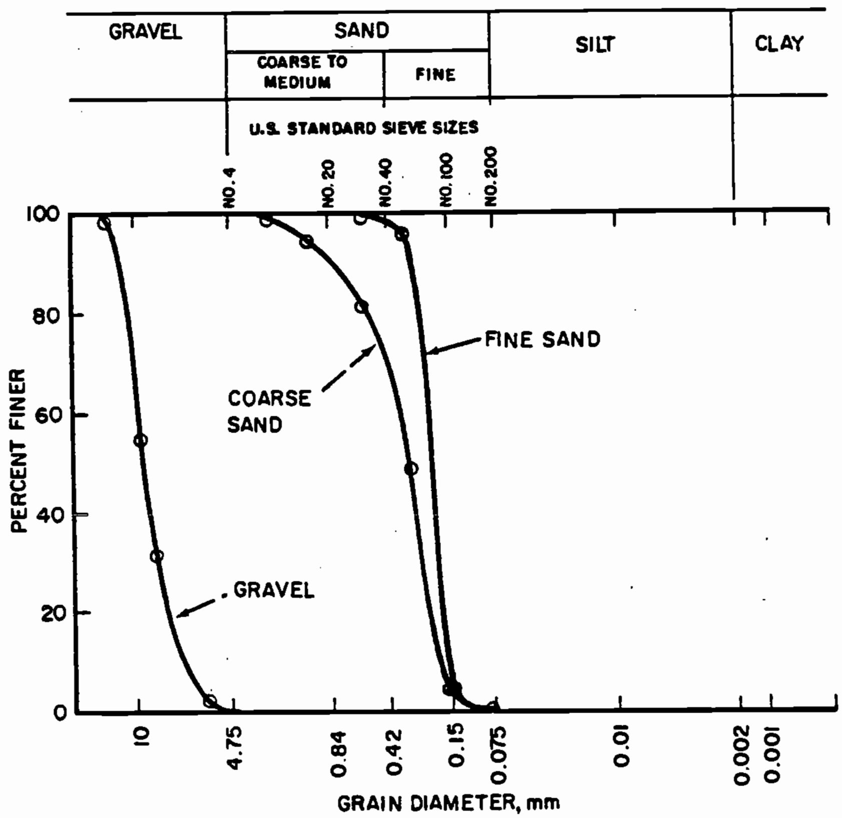


FIGURE 30. Particle size distribution for test gravels, coarse sands and fine sands used in sediment transport mixes for flume experiments at Kalama Springs, Washington.

TABLE 2: Intrusion variables evaluated during intrusion tests

FLOW

1: Supercritical; Discharge, Q = 41 l/s; Froude No., F = 1.3; Slope, S = .01

2: Subcritical; Discharge, Q = 36 l/s; Froude No., F = .4; Slope, S = .001

SEDIMENT MIX

Mix Proportions

Mix	1	2	3	4
Coarse Sand	1	2/3	1/3	0
Fine Sand	0	1/3	2/3	1

SEDIMENT INPUT VOLUME, RATE

low: 71 kg @ 157 kg/hr

high: 142 kg @ 157 kg/hr

gradation was determined by sieving with U.S. standard sieves.

The first 24 runs were designed to test the relative rate of intrusion of sands into the gravel test reach. Two flow conditions, one subcritical and one supercritical, were evaluated (Table 2). Four different size gradations of sediment input at the 157 kg/hr rate for a total input of 71 kg were evaluated and each sediment transport condition was replicated three times.

Eight additional runs were designed to evaluate the maximum extent of intrusion of the four sediment mixes for the two conditions of sediment transport. These runs were twice as long as runs 1-24 so that a total of 142 kg sediment were added to the flume.

During all runs, the concentration and composition of sediment in transport at one and six cm above the gravel bed was determined from samples obtained by siphoning off continuous samples of the discharge through 0.64 cm diameter nozzles. Siphon samples were dried and weighed and then sieved to determine particle size gradations.

Results

The total amount of intrusion, by weight (tests 25-32) is significantly ($p = 0.95$) greater in subcritical flow than supercritical flow. In these same tests, total intrusion is significantly greater ($p = 0.95$) with finer sediment mixes than coarser mixes (Table 3).

Intrusion rates (tests 1-24) were not significantly ($p = 0.95$) affected by either sediment mix or flow conditions except in the case of the 100% fine mix (Table 4). In this case, the rate of

TABLE 3: Total intrusion for high input volume tests

Test	Flow[a]	Sed mix[a]	Total intrusion, percent sand by weight Can 1	Can 2	Can 3	Average
25	1	1	6.3	6.2	7.4	6.6
26	1	2	8.1	6.6	7.2	7.3
27	1	3	8.2	9.3	12.3	9.9
28	1	4	21.5	21.5	22.0	21.7
29	2	1	12.9	12.3	12.6	12.6
30	2	2	19.2	14.9	22.2	18.8
31	2	3	16.9	12.5	17.2	15.5
32	2	4	26.6	26.5	25.3	26.1

[a] See Table 2.

TABLE 4: Intrusion for low input volume tests

Test	Block (replication)	Flow[a]	Sed mix[a]	Intrusion percent sand by weight Can 1	Can 2	Can 3	Average
1	1	1	1	8.2	7.4	3.9	6.5
2	1	1	2	8.8	7.1	10.4	8.8
3	1	1	3	9.1	8.5	8.6	8.7
4	1	1	4	8.9	8.1	8.8	8.6
5	1	2	1	2.6	3.0	2.1	2.6
6	1	2	2	11.1	6.0	5.7	7.6
7	1	2	3	16.0	11.9	16.9	14.9
8	1	2	4	23.0	23.0	18.8	21.6
9	2	1	1	6.3	8.4	9.4	8.0
10	2	1	2	6.8	6.2	7.7	6.9
11	2	1	3	7.4	6.1	7.8	7.1
12	2	1	4	9.1	7.6	7.6	7.1
13	2	2	1	7.0	4.2	6.8	6.0
14	2	2	2	9.0	12.3	5.4	8.9
15	2	2	3	7.3	6.1	12.0	8.5
16	2	2	4	22.4	24.4	23.2	23.3
17	3	1	1	8.8	8.1	6.0	7.6
18	3	1	2	6.0	6.6	7.6	6.7
19	3	1	3	7.9	4.5	12.6	8.4
20	3	1	4	9.4	8.0	7.9	8.4
21	3	2	1	8.1	8.5	8.6	8.4
22	3	2	2	7.9	11.2	9.5	9.5
23	3	2	3	7.7	9.1	7.1	8.0
24	3	2	4	23.7	23.9	23.2	23.6

[a]See Table 2.

intrusion was greater in the subcritical flow than in the supercritical flow. The lack of significant differences in intrusion rates in tests 1-24 may be the result of the inability to separate deep intrusion of fine sediment from accumulation of seal, or filter sized sediments. As sediment mixes became finer, the intrusion rate of sands which could seal the intergravel pores decreased, thereby making significant differences in total intrusion rates difficult to detect.

The particle size analyses of the rate tests (tests 1-24) show that the intruded sands are coarser than those in transport at either one or six cm above the gravels (Table 5). They are finer, however, than the coarse sand used in the sediment mixes. The particle size of the intruded sands corresponds closely with that of the input mix, which suggests that the filtered sands are an important component of the total intruded sand. Flow does not result in significant ($p = 0.95$) particle size difference in the measured size of intruded sand. Again, the analysis was unable to specifically illustrate particle size differences between deeply intruded fine sediments and seal sediments trapped near the surface of the gravel bed.

The particle size analyses of the total intrusion tests (tests 25-32) showed (Table 6) that sands which intruded in supercritical tests were significantly ($p = 0.95$) coarser than those which intruded in subcritical tests. The intruded sediments tended to become finer as the input mix became finer. The d_{85} of sands in the can samples was markedly coarser in the supercritical tests than in the

TABLE 5: Particle diameters for intruded sands in low input volume tests

Block (Source)	Flow[a]	Sed mix[a]	Particle diameter, mm d_{15}	d_{50}	d_{85}
1 (buried cans)	1	1	.23	.50	.85
1	1	2	.21	.38	.85
1	1	3	.20	.30	.60
1	1	4	.17	.22	.28
1	2	1	.21	.40	.84
1	2	2	.20	.32	.70
1	2	3	.16	.25	.53
1	2	4	.17	.22	.28
2 (1 cm siphon)	1	1	.16	.28	.60
2	1	2	.16	.25	.60
2	1	3	.15	.19	.30
2	1	4	.17	.21	.27
2	2	1	.21	.37	.66
2	2	2	.19	.30	.50
2	2	3	.15	.16	.28
2	2	4	.17	.22	.28
3 (6 cm siphon)	1	1	.15	.24	.37
3	1	2	.16	.23	.33
3	1	3	.15	.21	.30
3	1	4	.17	.21	.27
3	2	1	.14	.21	.32
3	2	2	.14	.20	.30
3	2	3	.16	.25	.35
3	2	4	.19	.29	.40

[a]See Table 2.

TABLE 6: Particle diameters for intruded sands in low input volume tests

Block (Source)	Flow[a]	Sed mix[a]	Particle diameter, mm d_{15}	d_{50}	d_{85}
1 (buried cans)	1	1	.22	.48	.90
1	1	2	.19	.33	.84
1	1	3	.17	.27	.76
1	1	4	.18	.21	.28
1	2	1	.20	.30	.57
1	2	2	.16	.24	.53
1	2	3	.15	.20	.42
1	2	4	.17	.23	.30
2 (1 cm siphon)	1	1	.20	.39	.67
2	1	2	.17	.27	.65
2	1	3	.18	.29	.42
2	1	4	.16	.21	.27
2	2	1	.21	.36	.69
2	2	2	.23	.42	.75
2	2	3	.20	.31	.59
2	2	4	.17	.23	.31
3 (6 cm siphon)	1	1	.14	.23	.35
3	1	2	.15	.22	.33
3	1	3	.15	.25	.32
3	1	4	.16	.21	.27
3	2	1	.15	.22	.33
3	2	2	.12	.17	.50
3	2	3	.15	.20	.33
3	2	4	.15	.20	.30

[a]See Table 2.

subcritical tests. This suggests that the effect of increasing the flow was to increase the dispersion of fine sands into the flow relative to the coarse sands. This resulted in a greater proportion of coarse (filterable) sands compared to fine (intrudable sands) in the flow immediately above the streambed. The ratio of the 6 cm to 1 cm siphon catches also indicated that considerably greater dispersion of sediments occurred during supercritical tests than subcritical tests.

The effect of changes in the relative proportion of coarse to fine sands near the streambed seems to result in changes in the relative rate of intrusion of the two sand sizes. The percent intrusion of fine sand in the rate tests was almost 2-1/2 times greater in subcritical than in supercritical flow (Table 3) while the percent intrusion of coarse sand was not significantly ($p = 0.95$) affected by the flow.

Discussion

The rate of intrusion and the rate of seal formation are functions of two conditions:

1. the concentration of intrudable and filterable particles at the gravel bed-streamflow interface,

2. the settling velocity of the sediment particles.

Only condition 1 was variable in the intrusion experiments. More turbulent flow in this case caused a greater dispersion of the finer sands vertically in the flow and resulted in a decrease in the concentration of the finer sands relative to the coarser sands at the flow-streambed boundary. Therefore, less intrusion occurred prior to the formation of a filter seal.

It should be noted, however, that other conditions could exist where filterable sediments would be relatively more affected by increased turbulent mixing than intrudable sediments. For example, in a situation where clays or silts, already uniformly dispersed throughout the flow, are the intrudable sediments, and very fine sands exhibiting increased concentrations with depth are the filterable sediments, it is possible that increased turbulence will result in an increase in the ratio of intrudable to filterable sediments at the streambed and an increase in the rate and extent of intrusion.

The results of the intrusion experiments are not directly applicable to natural streams. However, they do illustrate factors and processes to be considered in assessing the probable magnitude of fine sediment intrusion into stable streambed substrates. Several factors need to be considered:

1. The particle size distribution -- or preferably, the pore size distribution -- of the stable substrate materials (organic and inorganic).

2. The particle size distribution of sediments -- suspended and Phase I bedload -- in transport immediately above the streambed.

3. The concentration, by particle size class, of the sediments in transport immediately above the streambed.

Three general situations can apparently occur in a natural stream. First, if the substrate pores are small compared to sediments in transport, little if any intrusion may occur. If only very fine sediments (e.g., clays) can physically intrude, their slow settling velocities will preclude high rates or total amounts of intrusion unless the concentrations in transport are very high and persist for long periods of time. Second, if most sediments in transport are intrudable, intrusion will increase as a function of sediment concentration and duration of transport. Such conditions could conceivably exist at moderate flows over coarse streambeds when sediment transport is predominately suspended material and possibly very fine Phase I bedload. The third situation would be one in which the sediment in transport is comprised of both filterable and intrudable particles. In this case intrusion will increase when the ratio of intrudable to filterable sediments in transport near the streambed increases. This ratio of concentrations may be affected either by flow conditions or changes in the composition of sediment in transport.

It is impossible to generalize the probable effects of land use activities on the sediment intrusion process. However, watershed variables which affect the sediment regime of streams may affect the intrusion process by

1. altering the size composition of suspended sediment and Phase I bedload in transport,

2. altering the concentrations of suspended sediment and Phase I bedload in transport,

3. altering the duration of transport,

4. altering the particle size composition of the streambed,

5. altering the hydraulic conditions of the streamflow.

Site specific analysis of the intrusion variables would be necessary to determine whether such changes would result in increases, decreases, or no change in the intrusion process and the subsequent composition of channel substrates.

Desposition Experiment

Introduction

The deposition experiment was designed to examine the conditions during which streambed deposition occurs and how these conditions affect the particle size composition of the streambed. The field studies at Flynn Creek demonstrated that at discharges exceeding bankfull discharge, the streambed may undergo at least one cycle of scour and redeposition. The composition of the streambed is largely determined during the time of its deposition. Even subsequent changes in composition due to the intrusion of fine sediments is determined, in part, by the composition of bed material deposited at high flows.

Among the deposition variables that are hypothesized as affecting the particle size composition of streambed sediments are (1) the particle size composition of the bedload sediment in transport at the time of deposition, and (2) the rate of bedload transport during deposition. The literature, however, is characterized by an absence of field or laboratory studies of the deposition process. A systematic study of the variables affecting deposition is not easily performed in the field because scour and fill occur relatively infrequently and there is no way to control the conditions of deposition. Therefore, a flume study of bed material deposition was undertaken. While a flume is a simplification of a natural stream segment, it does provide an opportunity to control certain variables in the deposition process and obtain insight into how these variables affect deposition in a natural stream. The objectives of the deposition experiment were to:

1. determine the relationship between the particle size distribution of bed material in transport during deposition and the particle size distribution of the resultant streambed deposit, and

2. determine the effect of bedload transport rate and rate of deposition on the particle size distribution of streambed deposits.

Methods

The flume at the Kalama Springs Field Laboratory which was used for the sediment intrusion experiments was also used for the bed material deposition experiments. The flume was lengthened to include a test reach in which deposition would occur (Fig. 31). The back gate of the existing test reach was removed and the floor mats

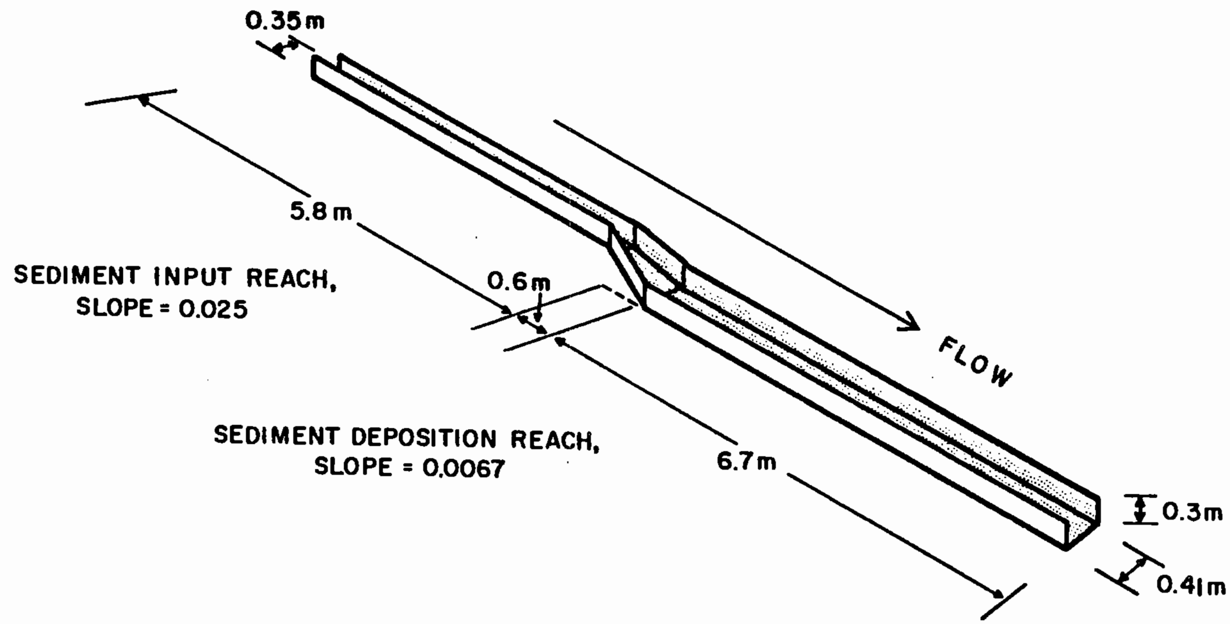


FIGURE 31. Flume used in deposition experiments.

serving as hydraulic roughness in the original channel were removed. An additional 5.5 m of flume were added to the downstream end of the existing flume. The width of the flume addition was 41 cm. The increase in width from the 35 cm width of the original flume was accomplished by a gentle flaring of the flume bottom and sides. The slope of the flume addition was 0% and the hydraulic roughness of the addition was increased over that of the original flume by placement of the floor mats on the bed.

The pre-test hydraulic conditions in regions of uniform flow in the original and modified flume reaches are summarized in Table 7. In the transition between the two flume reaches flows were supercritical, but "jumped" to subcritical condition upon entering the new test reach. Hydraulic conditions during the tests were allowed to adjust in response to the sediment transport and depositional conditions during the test. Hydraulic conditions over the deposition features at the end of each test are presented in the results section.

Once flows had been started, sediment mixes were manually added to the upstream flume section. Flow conditions at that point in the flume were sufficient to transport all sediments. In the downstream test reach, under conditions of decreased slope, increased width and increased hydraulic roughness, flows were not sufficient to transport all the sediments at the rate at which they were being added upstream. Thus, deposition occurred. After the sediment was added to the flume, flows were continued until the deposited sediments

TABLE 7: Average hydraulic conditions in regions of uniform flow for riffle deposition experiments

Location	Discharge Q, ℓ/sec	Width W, cm	Depth d, cm	Area A, cm^2	Hydraulic Radius R, cm	Velocity Vave, m/s	Slope S, m/m	Froude # $V / \sqrt{gy}$	Mannings "n"
Flume, Upstream	36	35.6	10.8	384	6.7	.94	.025	.92	.009
Flume, Test Reach	36	40.6	12.7	516	7.8	.70	.0067	.63	.02
Over Stable Riffles	36	40.6	7.9	320	5.7	1.28	.027	1.5	.02

armored with the larger bed material and transport in the test reach approached zero.

Four size gradations of bedload were evaluated by pre-mixing varying proportions of gravel and coarse sand used in the intrusion experiments (Fig. 30). The volume of gravel input was held constant at 88 l. Sand-to-gravel ratios of 1:1, 2:1, 3:1, and 5:1 and two sediment input rates of 20,000 kg/hr-m width and 6,660 kg/hr-m width were evaluated; each test had two replications.

The following information was recorded for each deposition feature (to be referred to as test "riffles"):

1. Length of time to riffle stability.
2. Water surface profile at termination of test.
3. Riffle longitudinal profile.

In addition, three subsamples of the riffle were extracted by inserting a sample frame into the riffle and removing the contents by hand. Riffle samples were subsequently dried and the percent sand in the sample was weighed. Samples were also sieved to determine the particle size gradation.

Results

The particle size gradation of the four sediment mixes were compared to the average particle size gradation of the resultant test riffle features formed under conditions of both high and low rates of sediment input (Fig. 32). The particle size curves meet at the

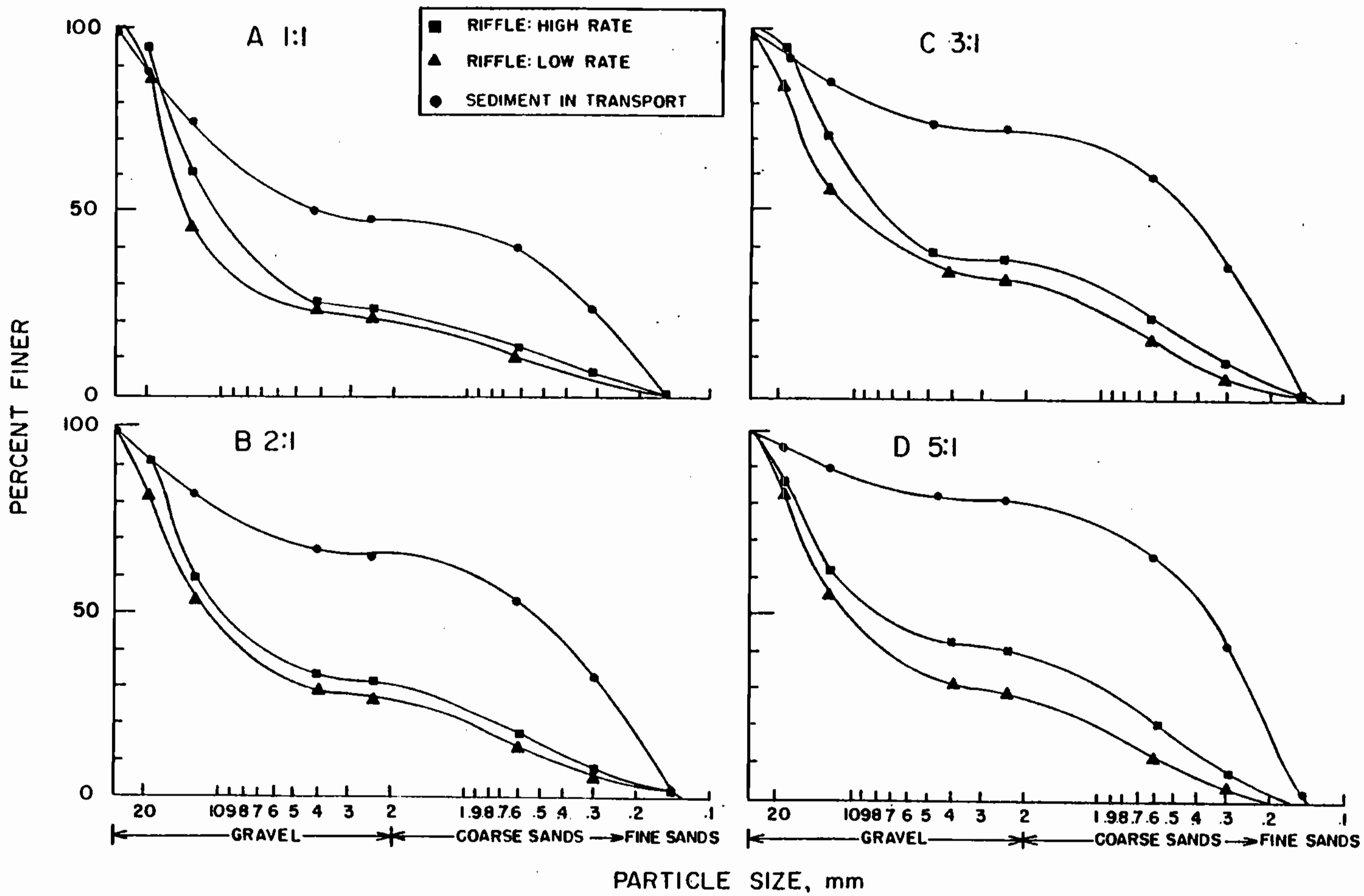


FIGURE 32. Particle size distributions of four sediment mixes and the average particle size distributions for the resultant test riffles formed under conditions of both high (20,000 kg/hr/m width) and low (6,600 kg/hr/m width) rates of sediment transport.

coarse and fine ends, indicating that the range of particle sizes of the sediment in transport is the same as the range of particle sizes in the riffle sediments. In all tests, however, the average particle size of the riffle sediments is considerably coarser than that of the sediments in transport. Furthermore, as the sediment mix in transport became finer, the coarseness of the riffle relative to that of the sediment in transport became greater (Fig. 33).

The average composition of the riffle is affected by the rate of sediment input (Fig. 32), and thus, the rate of riffle formation. Test riffles formed under conditions of lower sediment transport are more coarse, in all cases, than those formed under the higher rate of sediment transport.

Comparing the composition of the various test riffles presents less dramatic differences than those between riffle and transported sediments. While the percent sand increases exponentially with an increase in percent sand in transport (Fig. 34), the increase is small for the range of sediment mixes tested. Only sample location one in the high input rate tests shows large increases in the sand/gravel ratio in the riffle. The reasons for this difference are not known, and, except for this one case, the ratio of sand in transport and sample locations did not greatly affect the relationship between percent sand in transport and percent sand in the riffle.

When the d_{50} of the riffle material is plotted against the sand/gravel ratio in transport, a weak but significant ($p = 0.95$)

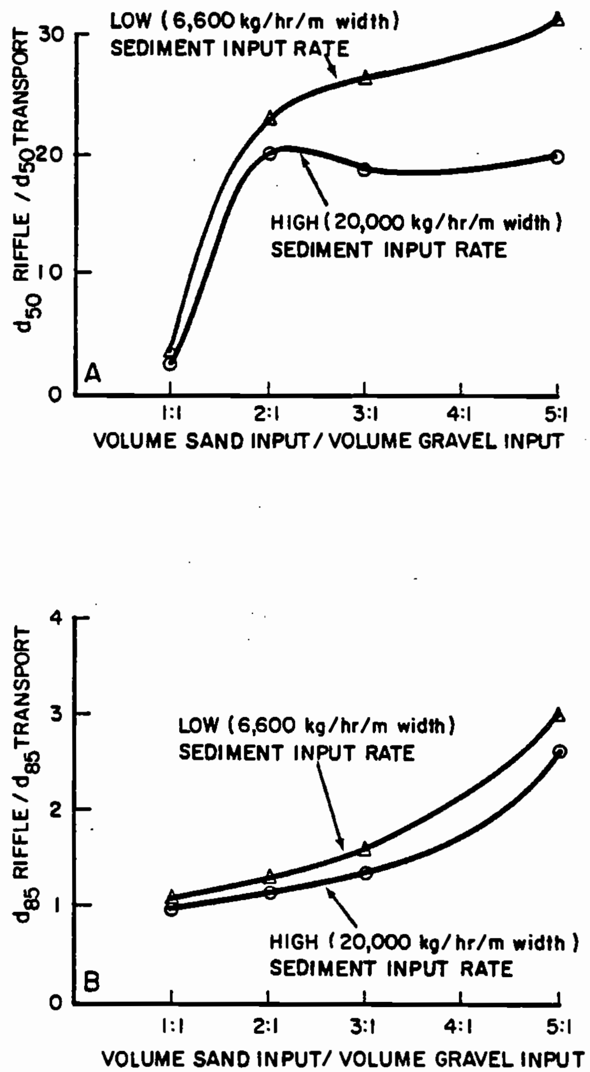


FIGURE 33. Ratio of (A) d_{85} riffle to d_{85} bed material in transport and (B) d_{50} riffle to d_{50} bed material in transport, both as a function of the ratio of sand to gravel in transport.

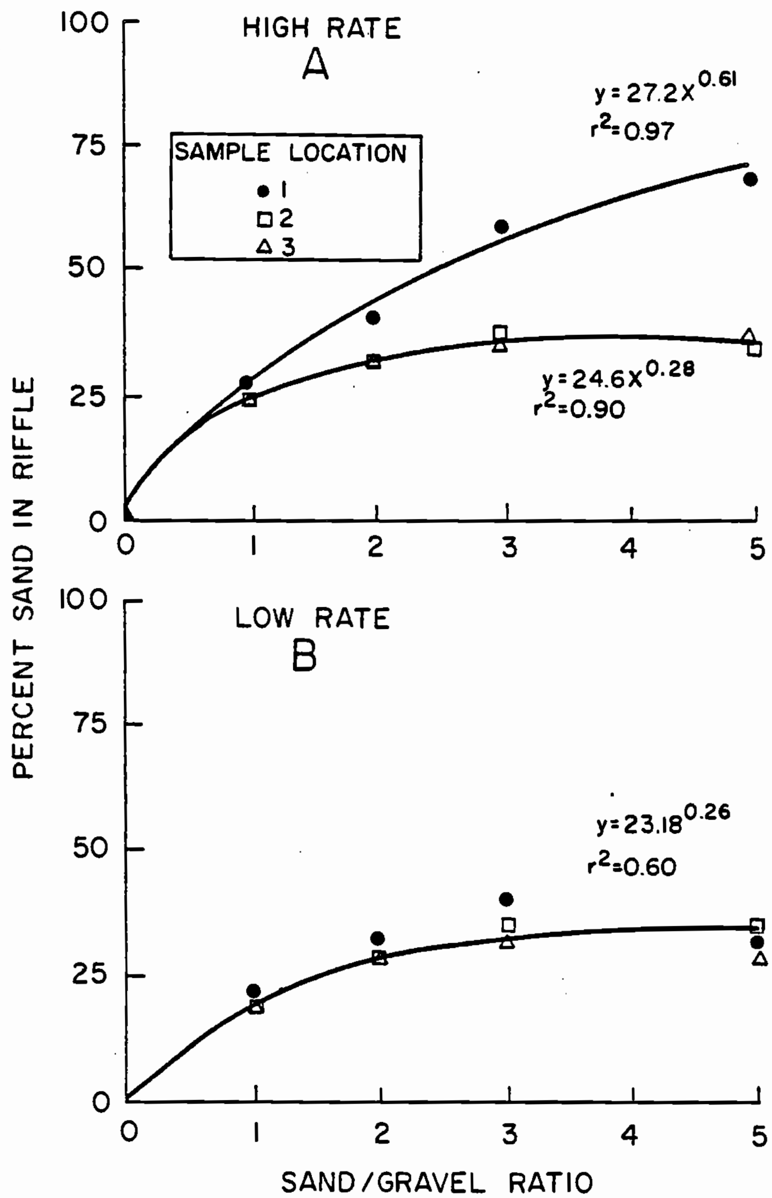


FIGURE 34. Percent sand by weight in test riffles versus the ratio of sand to gravel in transport.

decrease in the d_{50} of the riffle material occurs as the sand/gravel ratio of material in transport increases (Fig. 35).

No consistent changes in the longitudinal profiles of the test riffles occured as the sand/gravel ratio of transported material increased (Fig. 36). Figure 36 also presents average hydraulic conditions at incipient riffle stability for the deposition tests. The test riffles were all thickest at the upstream end and sloped downstream at an average of 0.027 m/m. The water surface slope paralleled the riffle slope. The time to riffle stability (armoring) increased as the percent sand in transport increased. The test riffles made with the five parts sand to one part gravel mix were smaller than the other riffles. An analysis of the deposition efficiency of the sand and gravel, i.e., the volume of sand and the volume of gravel in the riffle divided by the corresponding volumes of sand and gravel in the riffle divided by the corresponding volumes of sand and gravel input into the flow and expressed as a percent, showed no distinct trends, but did show a wide range of deposition efficiencies. The highest gravel deposition efficiency occurred when the two parts sand to one part gravel mix was input at high rates. The efficiency of gravel deposition was 60%. The lowest gravel deposition efficiency was 19%. This occurred when the five parts sand to one part gravel mix was input at low rates. Sand deposition efficiency ranged from a high of 17% when the 1:1 mix was input at high rates to a low of 2% when the five sand to one gravel mix was input at low rates.

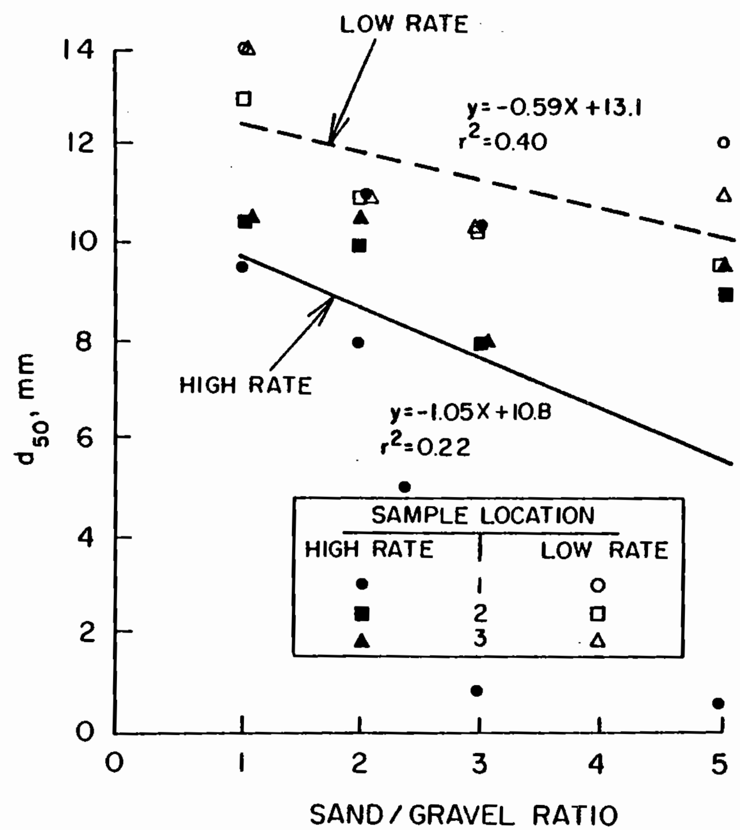


FIGURE 35. Median particle diameter (d_{50}) of riffle sediments as a function of the ratio of sand to gravel in transport.

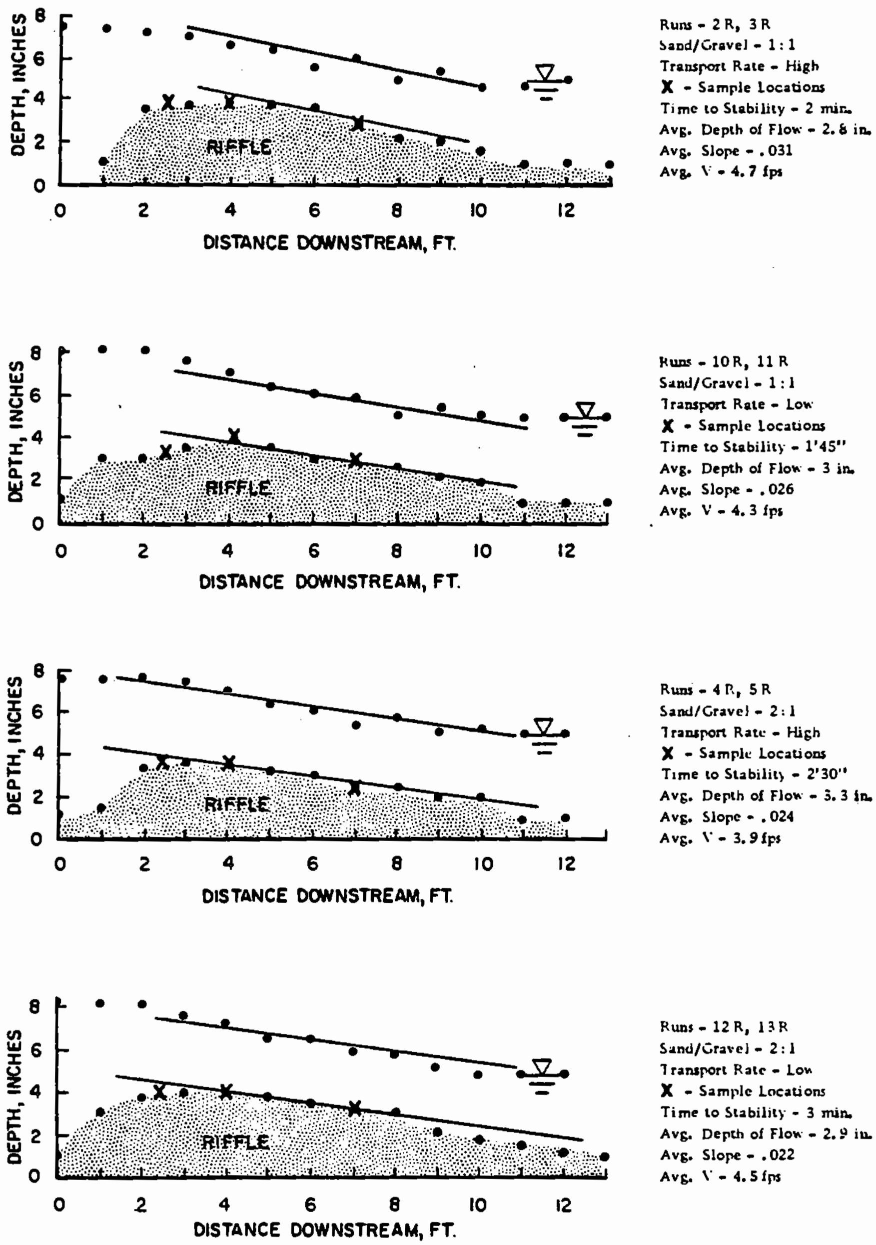
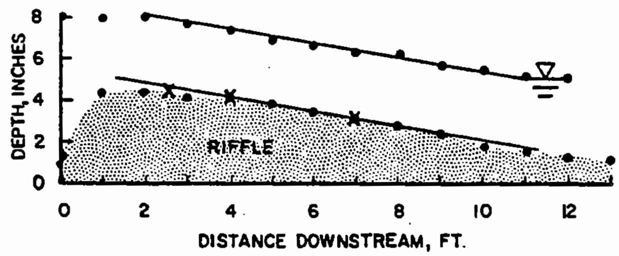
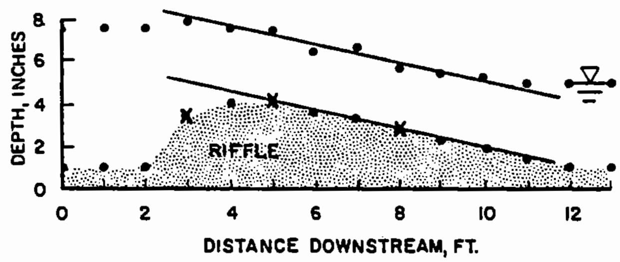


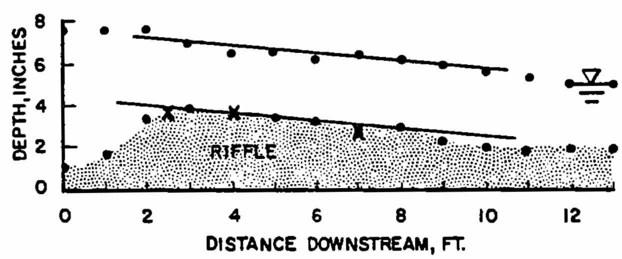
FIGURE 36. Average longitudinal profiles of stable test riffles and average sediment transport conditions during deposition.



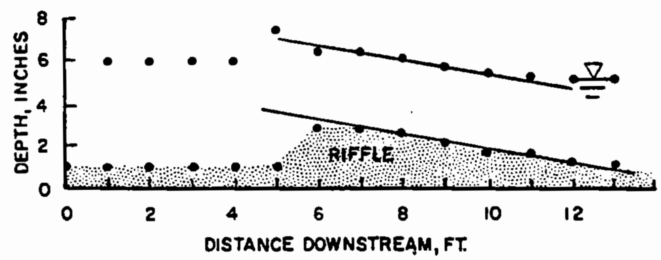
Runs - 6 R, 7 R
Sand/Gravel - 3:1
Transport Rate - High
X - Sample Locations
Time to Stability - 3'45"
Avg. Depth of Flow - 3.1 in.*
Avg. Slope - .030
Avg. V - 4.2 fps*



Runs - 14 R, 15 R
Sand/Gravel - 3:1
Transport Rate - Low
X - Sample Locations
Time to Stability - 3'45"
Avg. Depth of Flow - 3.2 in.
Avg. Slope - .037
Avg. V - 4.1 fps



Runs - 8 R, 9 R
Sand/Gravel - 5:1
Transport Rate - High
X - Sample Locations
Time to Stability - 5'55"
Avg. Depth of Flow - 3.2 in.
Avg. Slope - .016
Avg. V - 4.1 fps



Runs - 16 BR, 17 BR
Sand/Gravel - 5:1
Transport Rate - Low
X - Sample Locations
Time to Stability - 8 min. plus
Avg. Depth of Flow - 3.6 in.
Avg. Slope - .030
Avg. V - 3.6 fps

* 1 in. = 0.024 m
1 fps = 0.31 m/s

FIGURE 36 (Continued).

Discussion

The results of this study showed that the particle size gradation of the test riffles was not particularly sensitive to increased proportions of fine bed material in transport at the time of deposition. The results suggest that, for a given flow condition, the range of bed material sizes in transport--as determined by the largest particles to be transported--and the rate of bedload transport may be more important variables affecting the particle size composition of riffle features. The result of increasing the proportion of fine bed material in transport was to decrease the armoring efficiency of the test riffle and to decrease the deposition efficiency of the sand relative to that of the gravel.

While the test riffles are considerably coarser than the sediment mix in transport, the range of sediment sizes in the test riffles was the same as the range of sediment sizes in transport at the time of deposition. This is similar to what was found during riffle deposition during the field studies at Flynn Creek.

It is interesting to note that, even using the coarsest sediment mix, the percent sand in the riffle features was greater than that found in the intrusion experiments. This suggests that, in certain cases, the composition of streambed substrate upon deposition precludes significant subsequent intrusion of sand-sized materials into the stable streambed.

While the results of this experiment are not directly applicable to natural streams, there is some reason to suggest that increased levels of fine bed sediments in transport alone will not result in major changes in the composition of gravel riffles but, instead, will result in the increased deposition of fine sediments in other locations in the stream channel.

There is a great need for further research into the deposition process. The effect of sediment transport rates, and the range and gradation of the sediment particle sizes in transport on deposition efficiency under different hydraulic conditions is poorly understood. In addition, the role of the largest sediment sizes in transport in controlling the geometry and particle size composition of riffles needs to be investigated. While an increased delivery of fine bed sediments to alluvial stream channels may result in an increase in deposition of fine bed sediments in the channel, riffle composition may be more directly affected by those factors which influence the amount and size of the largest sediments available for transport. These factors may include external controls to channel slope and the rate and particle size composition of bed material delivered to the channel.

Riffle Stability Experiment

The riffle stability experiment was designed to determine the effect of Phase I bedload sediment transport on the stability of bed features, such as riffles, which are formed during Phase II transport. During the deposition experiments it was noted that increased proportions of fine sediment in transport increased the time necessary for riffle features to become stable. It was also observed that once a test riffle became stable it could again be made unstable by adding sand-sized bed material to the flow. Several researchers, most notably Vanoni (1941), Einstein (1944) and Leopold and Maddock (1953) have suggested that increased rates of sediment in transport near the bed increase the capability of the flow to transport bed sediments and scour the streambed. In the design of stable channels, however, it is often considered that increased concentrations of suspended sediment in transport result in increased stability of the channel (Chow, 1959).

The objectives of the riffle stability experiment were to:

1. examine the effect of increased duration of fine bedload sediment transport on the stability of a test riffle,

2. examine the effect of increased rate of fine bedload sediment transport on the stability of a test riffle.

Methods

The riffle stability experiment was conducted using the same modified flume that was used in the riffle deposition experiments. Flow conditions also remained unchanged (Table 7).

A riffle was created in the test reach by using 176 l.(1:1 sand to gravel mixture) used in the deposition experiments. The sediment was added at 6,600 kg/hr/m-width and the resultant riffle was allowed to armor. Coarse sand (Fig. 30) was then added to the flow and was transported over the previously stabilized riffle. Gravel-sized material which was removed from the test riffle was caught in a 4 mm mesh basket placed at the outfall of the flume. All exported riffle material was dried, then weighed.

Four volumes of sand were added to the flow at two different rates (20,000 and 6,600 kg/hr/m-width). Each test condition was replicated twice. Each test riffle was used for one series of four stability tests involving one input each of 35, 70, 105 and 140 kg of sand, respectively. Following each trial, the riffle was reformed by adding 35 kg of the gravel-sand mix at the rate of 6,600 kg/hr/m-width and the riffle was then allowed to restabilize.

Results and Discussion

Results indicate that relatively high rates of sand in transport result in destabilizing a riffle which is stable under conditions of zero sediment transport (Fig. 37). The weight of riffle material exported from the riffle is also shown to increase with the volume of sand transported over the riffle. However, no significant differences between gravel export and the rate of sand transport were detected.

A relatively large variation in gravel export occurred between replications--particularly with regard to the low input rate, low volume input tests. This situation makes it difficult to detect significant differences in gravel export resulting from the different rates of sand transport. It is hypothesized, however, that as

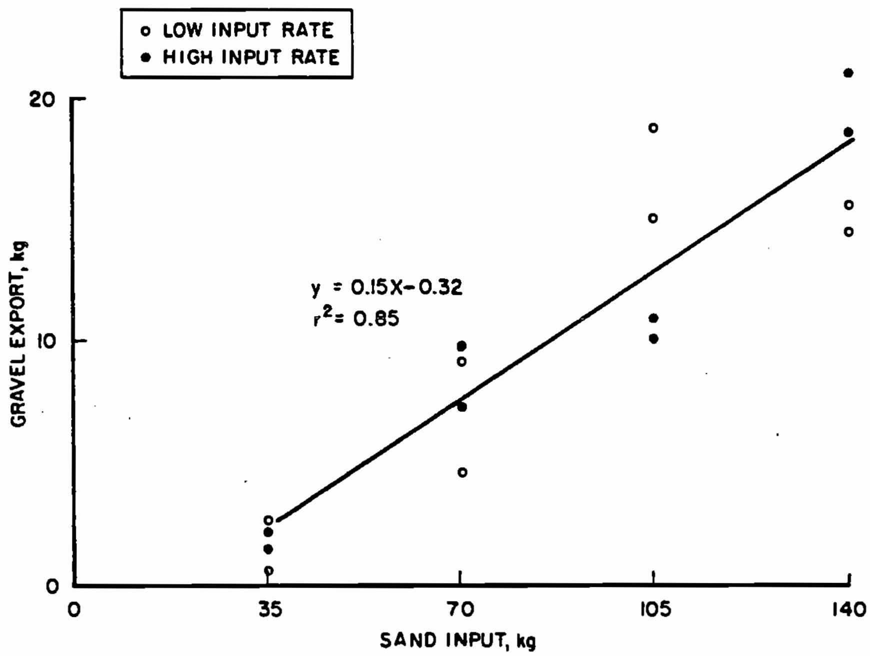


FIGURE 37. Gravel export versus sand input. Riffle stability experiment, Kalama Springs, Washington.

sand transport rates decrease and eventually approach zero, the corresponding export of riffle material should also decrease. The erratic behavior of the relationship between gravel export and sand input may result from several factors. First, the amount of riffle material exported, after large volume inputs of sand, was larger than expected. The size of the test riffle, and thus the availability of material for export, may have become limiting under conditions of high volumes of sand input. Second, disruption of the riffle armor could, at some point, have abruptly increased the ease with which riffle sediments were transported. Third, the replenishment of riffle gravels following individual runs may have been insufficient after runs in which large volumes of riffle material were exported.

The results of the riffle stability experiment have implications for natural streams. At high rates of Phase I bedload transport, the stability of riffle features may be decreased. Therefore, the initiation of Phase II bedload transport and the corresponding scour and redeposition of riffle features may depend, in part, upon the rate and volume of Phase I sediment in transport.

V. THE DESCRIPTIVE MODEL

The two-phase concept of bedload transport (Emmett, 1976), the theory of the velocity reversal (Keller, 1971), and the requirement for sediment continuity within any finite reach of stream channel (Colby, 1964) provide the basis for hypothesizing a descriptive model of bed material routing in small alluvial channels exhibiting sequences of pools and armored riffles. Several assumptions are inherent in the model. For example, flows are non-uniform and successive pool or riffle features do not necessarily have similar geometries. Riffles are comprised of coarser bed material than the pools and are armored.

As flows increase, Phase I bedload transport begins. The specific supply source of Phase I bed material is not easily defined, but it is not the bed material comprising the riffles. It is predominantly sand sized sediment that has settled out in pools, along channel banks and behind obstructions. Initially, Phase I transport may be non-uniform and occurs only from areas of relatively high bed shear stress to areas of relatively low bed shear stress. Local minor adjustments in channel geometry may result. Phase I transport rates may be direct functions of discharge, or they may be limited by sediment supply considerations.

As flows continue to increase, two things happen. First, the bottom velocity of the pool increases above that of the riffle and secondly, the riffle armor is disturbed. This second condition marks the beginning of Phase II transport. Flows are now in excess of those necessary to transport riffle sediments and riffle scour proceeds, provided the bedload transport capacity over the riffle is in excess of the bedload transport rates into the riffle section (Fig. 38). Because of the proportionately high bottom velocities in the pool, the riffle material is transported through the pool. It will begin to settle out when areas of decreased bedload transport capacity are encountered. This will happen at a downstream riffle which has lower shear stresses either because it has just undergone a scour sequence of its own, or because it has significantly slower flows due to differences in initial geometry. Deposition occurs at a riffle if rates of inflowing bed material are greater than the scour or transport capacity at the downstream riffle.

As long as bedload transport capacity is non-uniform in the downstream direction, the channel must be undergoing localized changes in bad material storage (Fig. 38). Under conditions of Phase II transport, it is suggested that riffles are the bed material features with storage volumes most responsive to spatial variations in bedload transport. In this case, Phase II bedload transport can be conceptualized as a "leap-frogging" of bed material downstream from riffle to riffle.

In theory, riffle scour and deposition would occur until, at any given flow, the transport capacity over all riffles was uniform.

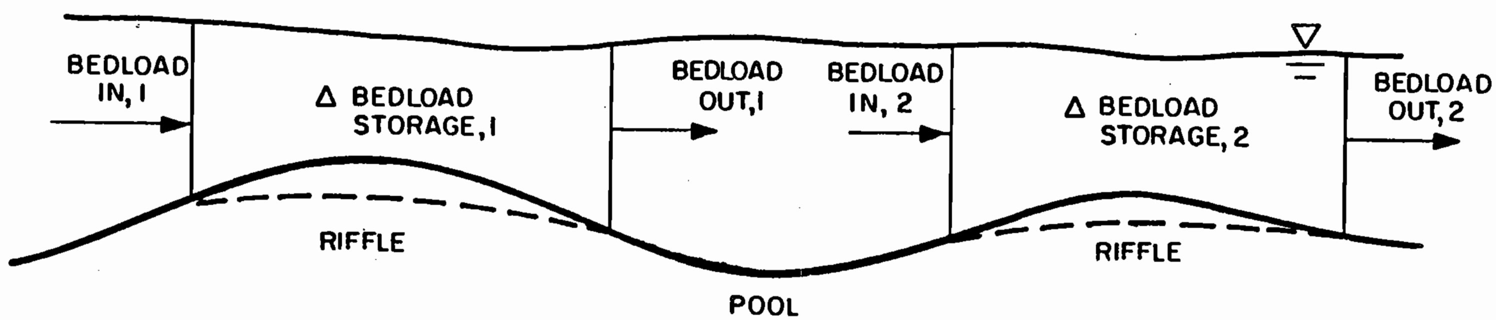


FIGURE 38. Definition sketch for a descriptive model of bedload routing.

Two factors make the attainment of uniform Phase II transport unlikely. First, channel geometries in many mountain streams are highly irregular, even at successive riffle features. Therefore, velocity vs. discharge relationships would be different at each riffle and rapidly varying changes in discharge would result in new conditions of non-uniform bedload transport capacity at successive riffles. Second, non-uniform inputs of sediment or debris from channel banks or hillslopes may cause local perturbations to channel geometries or sediment supplies and may result in new conditions of non-uniform bedload transport.

While long-term average Phase II bedload transport rates may conceivably be approximated by semi-empiric relationships between discharge and some "average," or "representative" channel condition, the tendency is for the stream to perpetuate a dynamic equilibrium condition with regard to local geometries and conditions of bedload transport. The result is that Phase II bedload transport is, by nature, highly unsteady and non-uniform. Riffle scour and fill is an integral part of Phase II bedload transport.

The resulting composition of deposited riffle material will be a function of the rate and size gradation of the bed material in transport at the time of deposition.

A flow chart for a simple mathematical model of the two-phase system of bed material routing in alluvial channels is presented in Figure 39. The flow chart is presented for descriptive purposes

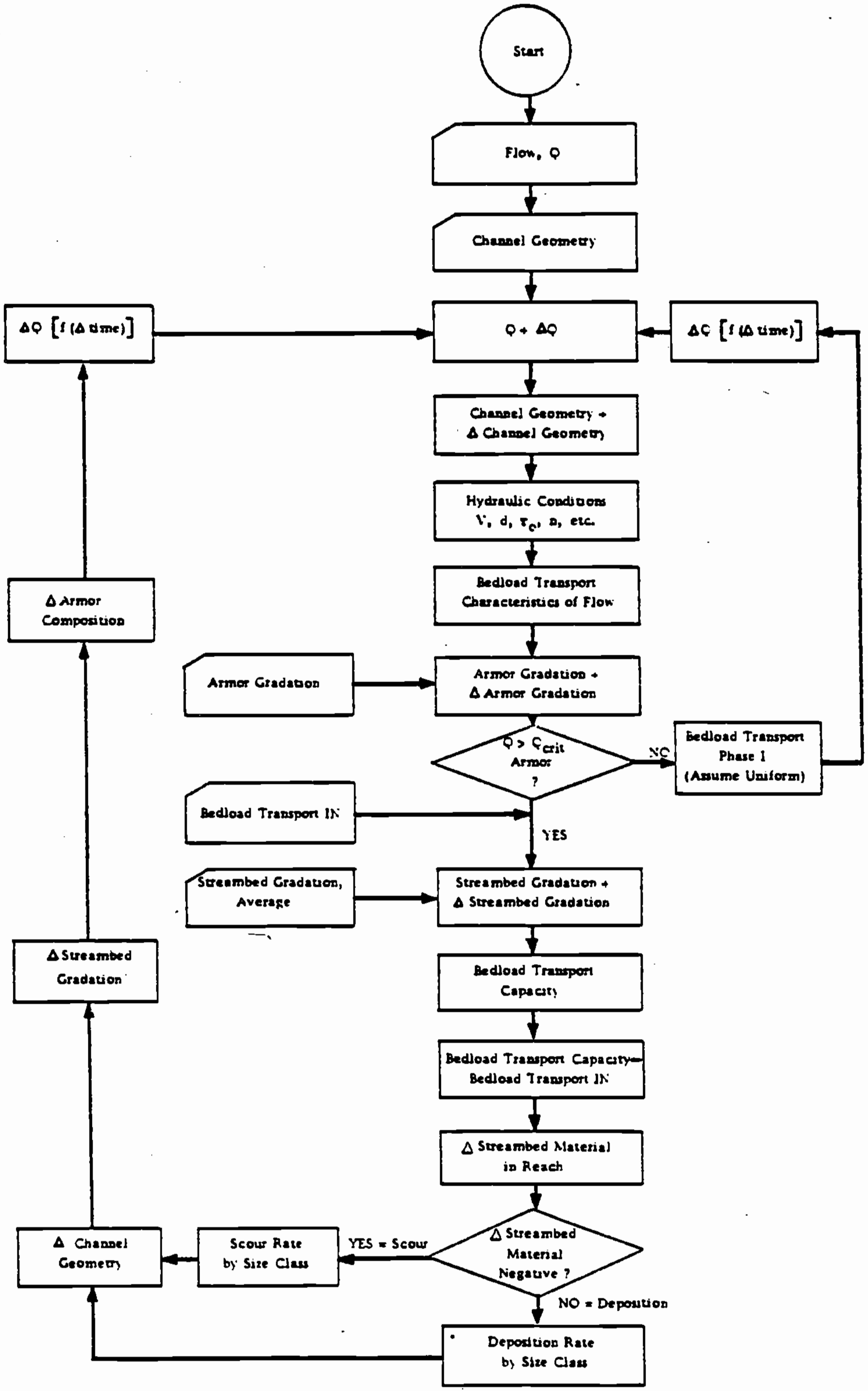


FIGURE 39. A flow chart for a two-phase model of bed material routing in alluvial channels.

only because it is believed that the state of the art is still inadequate to meaningfully apply such a model. Even if a procedure such as the Einstein bedload function can be assumed to accurately predict bedload transport, it is still not possible to represent the deposition of particles from transport under varying conditions of flow and sediment transport or to simulate the armoring process. At present, there are no data sets which provide a continuous time series of hydraulic conditions, bedload transport, bed elevation and bed composition which would be adequate for calibrating or testing a model with empirical coefficients. In addition, data do not exist which allow for a rigorous quantification of either Phase I or Phase II bedload transport in natural streams.

The flow chart illustrated in Figure 39 is general and methods of determining bedload transport, hydraulic conditions, etc. are not specified. Also, the desirable time increments for the iterative calculations are not specified. They will be dependent upon the quantitative methods chosen and the characteristics of the stream being modelled.

Possibly one of the greatest difficulties, however, in developing a mathematical model of bed material routing which accounts for local variables in transport and bed material storage would be in selecting useful scales in space and time for cataloging a bed material mass balance. While a riffle-by-riffle cataloging of the sediment mass balance may best correspond to the Phase II sediment transport process on a single storm basis, model errors would rapidly multiply in a downstream direction. However, a bed material mass balance based upon a larger spatial scale would likely correspond to a cumulative sediment transport imbalance over many years' time. Such a sediment mass imbalance may more closely correspond to larger watershed controls over channel geometry or sediment delivery than to the inherent non-uniform condition of sediment transport on a single storm basis.

VI. SUMMARY AND CONCLUSIONS

A descriptive model of bed material routing was developed for alluvial streams exhibiting sequences of pools and armored riffles. The model assumes that channel geometry, sediment transport competence and the availability of sediments for transport are all non-uniform in the downstream direction. Changes in sediment storage in specific channel locations result from instantaneous differences in sediment transport rates between different channel locations. The composition of bed sediments in storage changes as the result of either the intrusion of fine sediments into the pore spaces of stable gravel beds or as the result of streambed deposition during periods of active bedload transport.

Bed material routing is described as occurring in two distinct phases. Phase I involves the transport of bed material over stable riffles. Stream flows during Phase I transport are less than those required to entrain riffle armor sediments. The immediate source of Phase I bed material is deposits of fine (e.g., sand-sized) sediment in locations such as pools, and along channel edges. Phase II bedload transport occurs at flows which are greater than those required to entrain riffle armor and involves larger riffle sediments in addition to Phase I sediments.

Phase I bedload transport at Flynn Creek, Oregon, and Huntington Creek, Utah, was characterized by rates which increased as stream discharge increased. At Flynn Creek the power relationship between discharge and Phase I bedload transport was consistent between storms and between seasons. At Huntington Creek, however, Phase I bedload transport rates decreased over time at constant discharge, indicating a possible sediment supply control over sediment transport rates. Phase I transport exhibited considerable variability over time at both Flynn Creek and Huntington Creek. It was not possible to discern how much of this variability was due to sampling error and how much actually represented unsteady bedload transport. Phase I bedload transport at Flynn Creek can be expected to occur several times during a normal water year in conjunction with freshets. Discharges considerably less than bankfull are sufficient to transport Phase I sediments.

Phase II bedload transport occurs when flows become competent to entrain riffle armor sediments. At Flynn Creek this condition occurred only once in a two-year period and required roughly a bankfull discharge. Phase II transport at Flynn Creek was characterized by (1) sediment transport rates which were highly unsteady over time in relation to stream discharge, and (2) rapid, multiple cycles of riffle scour and redeposition at and shortly after the peak in stream discharge. Riffle scour corresponded to peaks in bedload transport rates. Large changes in bed material storage in riffles at high flows implies that Phase II bedload transport is highly non-uniform in the downstream direction, and highly unsteady over time at any location in the channel. This unsteady, non-uniform transport condition is assured by the non-uniform distribution of channel geometries, sediment transport competence and sediment availability in the downstream direction. Under conditions of Phase II bedload transport, riffles appear to be the bed material features with storage volumes most responsive to spatial variations in bedload transport. In this case, Phase II bedload transport can be conceptualized as a "leap-frogging" of bed material downstream from riffle to riffle. The scour and redeposition of riffles during Phase II bedload transport provides a mechanism for changes in the particle size composition of riffles.

The particle size composition of riffles is determined primarily during bed material deposition. Sampling at Flynn Creek indicated that a riffle contains the range of sediment sizes found in transport at the time of deposition but is coarser than the mix of sediment in transport. In a flume study of the deposition process, small but significant ($p = 0.95$) decreases in the median particle diameter of riffle sediments resulted as the sediment mixture in transport varied from a 1:1 to a 5:1 sand-to-gravel ratio. Increasing the proportion of sands in transport caused both the armoring efficiency of test riffles and deposition efficiency of sand relative to gravel to decrease.

If the particle size composition of riffles is to change during Phase I bedload transport, it must occur as a result of the intrusion of fine sediments into the pore spaces of riffle sediments. Intrusion was not demonstrated at either Flynn Creek or Huntington Creek. In a flume study, however, intrusion was shown to be selective towards finer sediments which cannot be filtered by sediments near the surface of the riffle. Intrusion was shown to decrease, or even cease, if filterable sediments block surface pores in the riffle substrate. Thus, the rate of intrusion is not only a function of the rate of deposition of intrudable sediments into the riffle substrate, but also a function of the rate of deposition of filterable sediments into surface pores. When the conditions for intrusion exist, intrusion is a function of two factors: (1) the pore size distribution of the riffle substrate, and (2) the particle size distribution and concentration of suspended and Phase I bedload sediments in transport immediately above the streambed.

The stability of riffles may be in part related to the concentration of Phase I sediment in transport in addition to flow conditions and riffle armor size. A flume study of riffle stability indicated that increased amounts of fine (sand-sized) sediments in transport decreased the stability of previously stabilized riffles.

The results of this study are not directly applicable to an analysis of expected channel response to increased sediment delivery. However, several general conjectures may be made:

1. An increase in the delivery of very fine, suspended sediments may not greatly affect the form or composition of alluvial

channels, except to the extent that these sediments may intrude into the pore spaces of stable substrates.

2. An increase in delivery of fine, sand-sized bed material may not greatly affect the composition of gravel riffles, but may settle out in pools, along channel banks, and behind channel debris barriers. This may possibly result in a hydraulic smoothing of the channel and subsequently increased rates of Phase I bedload transport, decreased riffle stability and a small decrease in the particle size composition of riffles.

3. An increase in the delivery of coarse bed material in addition to fine bed material may result in general streambed aggredation, altered hydraulic geometries, increased rates of bedload transport and changes in the particle size composition of channel substrates.

4. An increase in the competence of the channel to transport sediments--due to increased slope resulting from debris removal, increased peak flows, or from a smoothing of channel roughness--may result in an increase in the range of bed material sizes in transport. This in turn may result in increased rates of bedload transport and changes in the particle size composition of channel substrates.

Two implications of the study results for stream sediment sampling are implied. First, bedload sediment transport must be sampled intensively over time in order to characterize the temporal variability associated with Phase II transport. Second, pools and channel edges may be more sensitive than riffles to the increased delivery of fine, sand-sized bed sediments. This has important implications when trying to monitor the impacts of increased sediment delivery on alluvial channel systems.

Any attempt to predict the response of an alluvial stream channel to increased rates of sediment delivery requires a careful assessment of the expected particle size characteristics of the delivered sediments and a careful characterization of existing stream channel and sediment transport conditions.

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APPENDIX

APPENDIX I: Field Data for February 6-9, 1979, Runoff: Flynn Creek, Oregon.

A. Discharge, Stage, Streambed Elevation and Bedload Transport at Riffle Cross Section 2.

Sample No.	Q, m^3/s	Inorganic Bedload Transport kg/hr.	Stage, ft.	Time	Location, cm x 10* 6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38
					Depth to Streambed, cm																
10	.26	11	0.97	14:40	142.5	136.0	135.0	135.0	136.0	137.5	137.5	139.0	141.5	145.0	146.0	147.5	149.0	147.5	145.0	140.0	139.0
11	.32	9	1.10	19:45	143.0	136.0	135.0	135.0	136.0	139.0	139.0	139.0	141.5	145.0	146.0	146.0	149.0	148.0	146.0	140.0	140.0
12	.40	23	1.20	21:00	143.0	136.5	136.0	135.5	136.0	138.0	138.0	139.0	142.0	146.0	147.0	148.0	149.0	147.5	146.0	141.1	140.0
13	.50	42	1.36	22:10	143.0	136.0	135.0	135.5	136.0	138.0	138.0	139.0	142.0	146.5	147.0	148.0	148.0	145.5	141.0	140.0	140.0
14	.60	56	1.50	23:15	143.5	135.0	137.0	135.5	136.0	138.0	138.0	139.0	141.5	146.0	147.0	148.0	149.0	148.0	144.5	142.0	140.0
				Feb.7																	
15	.75	320	1.65	00:30	144.0	136.5	136.0	135.5	136.0	138.0	138.0	140.0	142.0	147.0	147.0	148.0	148.0	149.0	146.0	141.0	140.0
16	.95	167	1.90	01:40	143.5	137.0	135.5	135.0	136.0	137.0	137.0	137.5	138.0	149.0	137.0	137.0	138.0	142.0	145.0	143.0	136.0
17	1.34	439	2.30	04:00	143.0	137.0	136.0	135.5	136.0	139.0	143.5	145.0	144.0	143.0	152.0	140.0	142.0	143.0	143.0	134.0	130.0
18	1.46	1094	2.35	04:40	143.0	137.0	136.0	135.0	136.0	139.0	142.5	144.0	145.0	144.0	142.5	142.0	143.0	144.0	142.0	138.0	131.0
19	1.53	2426	2.50	06:00	142.0	136.0	136.0	135.0	136.0	138.0	144.0	149.0	154.0	154.0	156.0	160.0	164.0	166.0	162.0	144.0	133.0
20	1.53	2409	2.46	07:40	142.0	135.0	136.0	136.0	136.0	140.0	141.0	143.0	143.0	144.0	146.0	149.0	154.0	164.0	162.0	149.0	136.0
21	1.48	507	2.46	08:15	142.0	135.0	134.0	135.0	137.0	139.5	140.0	144.0	148.0	149.0	150.0	154.0	155.5	158.0	159.0	151.5	136.0
22	1.44	1505	2.38	09:45	139.0	135.0	135.0	136.0	137.0	139.0	145.0	150.0	151.0	153.0	154.0	157.0	159.0	160.0	159.0	152.0	138.0
23	1.32	236	2.28	11:50	138.0	134.0	135.5	135.5	137.0	140.0	146.5	149.0	151.0	153.0	152.5	154.0	156.0	158.0	157.0	155.0	140.0
24	1.19	87	2.19	14:10	137.0	133.0	135.5	135.5	136.5	141.0	145.5	149.5	151.0	152.5	152.0	153.0	156.0	157.0	156.5	152.0	139.0
25	1.14	161	2.11	15:50	138.0	133.0	135.0	136.0	137.0	142.0	146.0	149.0	153.0	153.0	152.0	153.0	156.0	157.0	157.0	153.0	141.0
26	1.06	286	2.05	17:55	135.0	132.0	135.0	135.0	137.0	140.0	146.0	150.0	153.0	153.0	153.0	153.0	155.0	157.0	157.0	152.0	140.0
27	.95	538	1.90	21:20	135.0	132.0	133.0	135.0	137.0	141.0	148.0	150.0	151.0	150.0	151.0	153.0	155.0	156.0	155.0	151.0	139.0
28	.89	728	1.82	23:45	135.0	134.0	133.0	135.0	137.0	141.0	148.0	150.0	151.0	151.0	151.0	150.0	153.0	156.0	155.0	151.0	139.0
				Feb.8																	
29	.63	56	1.50	13:10	134.0	131.0	132.0	134.5	137.0	141.0	148.0	150.0	150.5	152.5	153.0	153.0	154.0	156.0	157.0	153.0	140.0
30	.60	50	1.46	16:00	134.0	131.0	132.0	135.0	137.0	141.0	148.0	150.0	151.0	153.0	152.5	153.0	153.5	155.0	157.0	153.0	140.0
31	.58	59	1.45	17:00	134.0	131.0	132.0	135.0	137.0	141.0	148.0	150.0	151.0	152.0	153.0	152.5	153.5	156.0	157.0	153.0	140.0
32	.55	46	1.40	21:25	134.0	131.5	133.5	134.5	137.0	138.5	148.0	150.0	151.0	152.5	153.5	152.8	154.0	155.5	156.0	152.5	139.5
33	.54	34	1.40	23:20	135.0	137.0	133.0	135.0	137.0	142.0	147.0	150.0	151.0	152.0	153.5	152.5	154.0	156.0	155.0	153.0	139.5
				Feb.9																	
34	.51	36	1.36	07:20	135.0	132.0	133.0	135.0	137.0	138.0	147.0	150.0	151.0	152.0	153.0	152.5	154.0	156.0	155.0	152.5	140.0

* Location corresponds to distance from right bank (facing downstream)

right bank is at 60 cm

B. Discharge, Stage and Streambed Elevation at Pool Cross Section 1.

Sample No.	Q,m^3/s	Stage, Ft.	Time	Location, Ft.* 4D	41	42	43	44	45	46	47	48	49	5D
				Depth to Streambed, cm										
			Feb. 6											
10	.26	0.97	14:40		81	91	107	127	140	150	160	163	163	155
11	.32	1.10	19:45		81	94	109	130	142	157	160	163	142	150
12	.40	1.20	21:00		81	94	109	132	142	155	160	163	157	150
13	.50	1.36	22:10		81	91	107	140	145	155	160	160	157	147
14	.60	1.50	23:15		86	94	114	127	140	157	160	160	155	150
			Feb. 7											
15	.75	1.65	00:30		79	89	109	127	142	155	160	160	155	147
16	.95	1.90	01:40	61	81	91	112	124	135	152	160	160	157	150
17	1.35	2.30	04:00	61	79	94	99	104	117	127	130	137	147	155
18	1.46	2.35	04:40	66	66	91	99	112	119	130	135	142	147	152
19	1.53	2.50	06:00	58	61	94	94	102	109	127	140	147	147	152
20	1.53	2.46	07:40	61	76	99	102	112	172	132	152	157	152	140
21	1.48	2.46	08:15	61	79	109	102	107	119	132	145	152	150	140
22	1.44	2.38	09:45	58	76	102	99	109	117	127	142	155	152	152
23	1.32	2.28	11:50	63	81	104	102	108	122	132	145	157	152	152
24	1.19	2.19	14:10	69	79	94	102	104	109	122	132	145	153	157
25	1.14	2.11	15:50	58	79	94	102	102	112	127	137	152	157	152
26	1.06	2.05	17:55	71	76		99	102	112	127	140	150	157	152
27	.95	1.90	21:20	56	76	99	102	104	109	122	132	140	152	140
28	.89	1.82	23:45	69	79	99	104	104	109	124	132	150	157	152
			Feb. 8											
29	.63	1.50	13:10	69	76	104	104	109	114	124	132	147	155	152
30	.60	1.46	16:00		76	102	104	107	114	122	132	147	152	152
31	.58	1.45	17:00		76	104	104	107	117	124	135	152	152	152
32	.55	1.40	21:25		76	104	107	107	112	122	155	150	155	152
33	.54	1.40	23:20		76	104	107	107	119	124	140	159	152	152
			Feb. 9											
34	.51	1.36	07:20		76	104	104	109	114	124	135	145	137	152

* Location corresponds to distance from low water right bank (facing downstream) plus 40. (Low water right bank is at 41 ft.)

C. Water Depth in cm. at Riffle Cross Section 2.

Sample No.	Location, cm x 10* 6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38
10	21.5	15.0	14.0	14.0	15.0	16.5	16.5	18.0	20.5	24.0	25.0	26.5	28.0	26.5	24.0	19.0	18.0
11	24.5	17.5	16.5	16.5	17.5	19.5	20.5	20.5	23.0	26.5	27.5	27.5	30.5	29.5	27.5	31.5	31.5
12	27.0	20.5	20.0	19.5	20.0	22.0	22.0	23.0	26.0	29.0	30.0	31.0	32.0	30.5	29.0	25.0	24.0
13	32.0	25.0	24.0	24.5	25.0	27.0	27.0	28.0	31.0	35.5	36.0	37.0	38.0	37.0	34.5	30.0	29.0
14	38.5	31.0	32.0	30.0	31.0	33.0	33.0	34.0	36.5	41.0	42.0	43.0	44.0	43.0	39.5	37.0	35.0
15	42.0	34.5	34.0	33.5	34.0	36.0	36.0	38.0	40.0	45.0	45.0	46.0	46.0	47.0	44.0	39.0	38.0
16	51.5	45.0	43.5	43.0	44.0	45.0	45.0	45.5	46.0	47.0	45.0	45.0	46.0	50.0	53.0	51.0	44.0
17	63.0	57.0	56.0	55.5	56.0	59.0	63.5	65.0	64.0	63.0	62.0	60.0	62.0	63.0	63.0	54.0	50.0
18	65.0	59.0	58.0	57.0	58.0	61.0	64.5	66.0	67.0	66.0	64.5	64.0	65.0	66.0	64.0	60.0	53.0
19	67.0	61.0	61.0	60.0	61.0	63.0	69.0	74.0	79.0	79.0	81.0	85.0	89.0	91.0	87.0	69.0	58.0
20	64.0	59.0	60.0	60.0	60.0	64.0	65.0	67.0	67.0	68.0	70.0	73.0	80.0	88.0	86.0	73.0	60.0
21	65.0	58.0	58.0	58.0	60.0	62.5	63.0	67.0	71.0	72.0	73.0	77.0	78.5	81.0	82.0	74.5	59.0
22	59.0	55.0	56.0	56.0	57.0	59.0	65.0	70.0	71.0	73.0	74.0	77.0	79.0	80.0	79.0	72.0	58.0
23	56.0	52.0	53.5	53.5	55.0	58.0	64.5	67.0	69.0	71.0	70.5	72.0	74.0	76.0	75.0	73.0	58.0
24	52.0	48.0	50.5	50.5	51.5	56.0	60.5	64.5	66.0	67.5	66.5	68.0	71.0	72.0	71.5	67.0	54.0
25	51.0	46.0	48.0	49.0	50.0	55.0	59.0	62.0	66.0	66.0	65.0	66.0	69.0	70.0	70.0	66.0	54.0
26	47.0	43.0	46.0	36.0	38.0	52.0	57.0	61.0	64.0	64.0	63.0	64.0	66.0	68.0	68.0	63.0	51.0
27	42.0	38.0	39.0	41.0	43.0	47.0	54.0	56.0	57.0	56.0	59.0	59.0	61.0	62.0	61.0	57.0	45.0
28	39.0	37.0	36.0	38.0	40.0	44.0	51.0	53.0	54.0	54.0	54.0	53.0	56.0	59.0	58.0	54.0	42.0
29	28.0	25.0	26.0	28.5	31.0	35.0	43.0	45.0	45.5	47.5	48.0	48.0	49.0	50.0	51.0	47.0	34.0
30	27.0	24.0	25.0	28.0	30.0	34.0	41.0	43.0	44.0	46.0	45.5	46.0	46.5	48.0	50.0	46.0	34.0
31	26.0	23.0	24.0	27.0	29.0	33.0	40.0	42.0	43.0	44.0	45.0	44.5	45.5	48.0	49.0	45.0	32.0
32	24.5	22.0	24.0	25.0	27.5	29.0	38.5	40.5	41.5	43.0	44.0	43.5	44.5	46.0	46.5	43.0	30.0
33	25.5	22.5	23.5	25.5	27.5	32.5	37.5	40.5	41.5	42.5	43.5	43.0	44.5	46.5	45.5	43.5	30.0
34	25.0	22.0	23.0	25.0	27.0	28.0	37.0	40.0	41.0	42.0	43.0	42.5	44.0	46.0	45.5	42.5	30.0

* Location corresponds to distance from right bank (facing downstream).