SEDIMENT TRANSPORT APPENDIX

1 SEDIMENT TRANSPORT PROCESSES

1.1 General

The sediment cycle begins with the erosion of soil and rock in a watershed and transport of that material by surface runoff or by mass wasting. The transport of sediment through a river system consists of multiple erosional and depositional cycles, as well as progressive physical breakdown of the material. Many sediment particles are intermittently stored in alluvial deposits along the channel margin or floodplain, and ultimately re-entrained via bank and bed erosion. Total sediment loads consist of suspended load (the fine-grained fraction transported in the water column) and bedload (the coarse-grained fraction transported along the channel bed). The transport of sediment through the stream system depends on the sediment supply (size and quantity) and the ability of the stream to transport that sediment supply.

1.2 Sediment Transport Processes and Aquatic Habitat

The caliber, volume, and transport dynamics of sediment exert considerable control on channel form and geomorphic processes that create and sustain aquatic habitat in all river systems. Sediment caliber dictates what geomorphic features and associated habitat types (e.g., sand bed vs. gravel bed) will be characteristic of a given channel. Sediment volume can affect the stability of a channel, causing channel aggradation if the volume delivered is in excess of the transport energy available, and causing channel degradation if the volume delivered is less than the transport energy available. Sediment volume may also affect channel pattern and slope, with high volumes of coarse sediment resulting in relatively steep slopes, high width/depth ratios, and braided channel patterns[1].

Some degree of sediment mobility is critical for the ecological health of a stream system. Booth and Jackson[2] note that anadromous salmonids “depend on particular combination of water and sediment fluxes to maintain favorable channel conditions.” Most Pacific Northwest aquatic organisms have evolved within dynamic stream systems, in which pools, bars, and other habitat features are continually reworked and reformed. Physical habitat is created and sustained through processes such as the maintenance of pools and riffles, the formation of transient bars, side channels, and backwater areas, the deposition of spawning gravels, and the flushing of fines from bed substrate.

Sediment sorting through selective transport creates spawning habitat and quality habitat for benthic organisms, which in turn are food for aquatic species such as fish. The maintenance of pool-riffle sequence morphologies and the effective sorting of bed materials exemplifies balanced conditions of sediment caliber, hydraulic complexity, and transport energy that serve to generate and maintain quality aquatic habitat.

1.3 Sediment Transport and Stream Morphology

1.3.1 General

Sediment transport and storage count among the major interdependent variables that determine stream morphology. Many channel features, including depositional bars, riffles, and dunes are manifestations of sediment transport and storage. **Table G1** lists typical features and associated sediment transport characteristics for the seven basic channel types defined by Montgomery and Buffington[3]. Although a number of channel classification schemes exist, that of Montgomery and Buffington serves well for the purpose of examining the role of sediment transport in determining stream morphology.

As seen in **Table G1**, the characteristic features of various channel types are often, to a great degree, the product of the balance between sediment supply and transport. For instance, cascade and step pool channel morphology is maintained by the stability of large, relatively immobile bed materials[4]. Smaller bed material readily moves through these channels during lesser flow events. Such channels are considered to be in a sediment "supply-limited" state, meaning that only a relatively small amount of readily transportable sediment is available. In contrast, dune ripple channel morphology is indicative of a sediment "transport-limited" situation, in which transportable sediment is readily available, and equilibrium between sediment deposition and mobilization is established. Significant bed load transport occurs in dune ripple channels over a broad range of discharges, including relatively low flows. Plane bed and pool riffle morphologies include a mix of transport- and supply-limited characteristics, with the presence of depositional bars in pool riffle systems suggesting a tendency towards transport-limited conditions. Channel bars represent temporary sediment storage in the stream channel, and also represent the incipient floodplain that may become established if additional sediment is deposited on the bar and vegetation takes hold. Bedrock channels tend to be supply-limited, and alluvial materials tend to occur only in "shielded" areas such as scour holes and behind obstructions. However, in contrast to cascade channels or step-pool channels, bedrock channels may owe their supply-limited character to a current lack of large form-resistance elements such as large wood that would retain alluvial sediment. Colluvial channels are strongly influenced by hillslope processes, and the majority of long-term sediment flux from these channels appears to be the result of debris flows.

Table G1. Channel types, characteristic features, and corresponding sediment transport processes based on Montgomery and Buffington.[3]

Channel Type	***Characteristic Features***	***Corresponding Sediment Transport Processes***
Cascade	• "Disorganized" bed material typically consisting of cobbles and boulders • Small, irregularly spaced pools less than a channel width apart	• Large, bed-forming materials typically become mobile only in large flood events (i.e., 50-100 yr events) • Gravel stored in low energy sites is transported by lesser floods • Sediment conditions are probably supply-limited
Step Pool	• Discrete steps formed by large-diameter material separating pools containing finer materials • Pool lengths generally equal 1-4 channel widths	• Like cascade channels, large, bed-forming materials typically become mobile only in large flood events • Gravel stored in low energy sites is transported during lesser floods • Sediment conditions are probably supply-limited
Plane Bed	• Characterized by long stretches of featureless bed • Composed of sand to boulder sized materials (typically gravel to cobble)	• Seem to be a transitional state between sediment supply- and sediment transport-limited channel form
Pool Riffle	• Contain alternating topographic depressions (pools) and high points (bars and riffles) typically spaced 5-7 channel widths apart • Generally unconfined, with well-developed floodplains • Generally occur at moderate to low gradients • Substrate varies from sand to cobble (typically gravel)	• Display both sediment supply- and transport-limited characteristics, but the presence of depositional bar forms suggest that they are more transport-limited than plane bed channels
Dune Ripple	• Typically low gradient, sand bed channels containing relatively mobile dunes, bedload sheets, and ripples	• Sediment conditions transport-limited
Bedrock	• Bedrock bed • Often, some alluvial material stored in scour holes and behind obstructions	• Generally reflect a high transport capacity relative to sediment supply or current lack of large roughness elements for sediment retention capacity
Colluvial	• Small headwater streams founded on colluvial fill	• Weak or ephemeral fluvial transport • Long-term sediment flux from these channels appears to be dominated by debris-flows

1.3.2 Effects of Vegetation on Sediment Transport

Vegetation has a profound effect on sediment transport, from the supply of sediment delivered from the uplands to quality and quantity of sediment transported and stored in the channel. The strength and roughness created by vegetation on the channel banks and across the floodplain (or the lack of it) greatly affect channel geometry and flow hydraulics, thus influencing the processing of sediment. By increasing bank strength, particularly in medium- to fine-textured soils, vegetation makes possible the evolution of relatively deep, narrow channel cross-section and meandering plan forms. Through its influencing channel geometry, vegetation strongly affects channel complexity and capacity. Both of these characteristics in turn affect sediment transport. Channel complexity provides both form roughness that reduces the energy available for erosion and transport, and hydraulic complexity that causes sediment sorting during deposition. By limiting channel capacity, vegetation increases channel-floodplain interactions, thereby limiting the erosive energy at high flows and delivering finer sediments to the floodplain for capture, storage, and stabilization. Thus, the dynamic interactions among flow, sediment, vegetation, and energy build and maintain stream/floodplain ecosystems.

1.3.2.1 Effects of Large Wood on Sediment Transport

Large wood in streams increases hydraulic complexity, influencing the local velocity fluctuations that determine the scour and deposition of sediment, and because of its form roughness is extremely important for energy dissipation. In general, the presence of wood tends to increase the sediment storage capacity of a reach. Other effects of large wood include sorting of sediment sizes, inducing bar formation, inducing local scour, and causing sediment deposition in channels and on floodplains that provide for riparian vegetation colonization and forest flood plain development[5],[6],[7],[8]. Wood can actually "force" pool riffle and step pool channels by inducing the formation of pools, bars, and steps. In extreme cases, logjams may force the presence of alluvial beds in otherwise bedrock reaches. Log jams play a major role in sediment transport dynamics, as water and sediment stored behind jams can be rapidly released, creating transport events ranging from small sediment pulses to high magnitude sediment and debris-laden dam outburst floods.

1.3.3 Effects of Floodplains on Sediment Transport

Floodplains play a critical role in sediment transport in alluvial stream systems. By functioning as a 'relief valve' for the stream during high flow periods, floodplains dramatically reduce the flow energy focused within the active channel. Alluvial stream/floodplain systems tend toward establishing an equilibrium that balances the inputs of sediment into a reach with the outputs leaving the reach. This equilibrium is reached by adjustments in the channel form such that there is just enough energy present in the 'normal' high flow regime to maintain a balance between sediment deliveries and exports. A critical part of these energy relationships is the availability of the floodplain to accept flows that exceed the natural channel capacity. Typically, diking and other activities that restrict or eliminate floodplain connectivity disrupt the equilibrium, often leading to increased erosion within the diked reach, and excessive sediment deposition downstream.

Furthermore, during high flows, when the large majority of sediment transport occurs, vegetated floodplains tend to efficiently trap and store fine sediments. This stream/floodplain interaction is part of a positive feedback loop that develops the conditions for a vigorous riparian/floodplain plant community, builds banks, shapes channel geometry, and attenuates flows. All of these processes and system characteristics exert a strong influence on the transport of bed load.

1.3.4 Effects of Dams and Weirs on Sediment Transport

The trapping of sediment behind dams and weirs (e.g., in sediment detention basins) often results in the release of sediment-deficient water from the structure. In effect, as long as a weir or dam acts as a sediment trap, it produces a "decoupling of the sediment transport conveyor belt."[9]. As a result of the decreased sediment load, erosion and armoring (hardening of bed with immobile, large substrate) of the channel bed downstream of dam or weir often occurs, as smaller-sized materials are winnowed from the bed and are not replaced[10]. Below large dams, this bed immobility is further accentuated by the controlled release of water, which mutes peak flows. Bed armoring can be preceded by incision if the size and gradation of the native bed material is small relative to hydraulic forces (i.e., if a great deal of fine material is winnowed out in the armoring process). Such incision is more likely in pool riffle, plane bed, and dune ripple reaches, where bed materials are more readily transported under average to moderately high discharges, than in steeper step pool and cascade reaches where the key bed elements are stable at relatively high discharges.

2 SEDIMENT TRANSPORT ANALYSIS

2.1 General

Sediment transport is one of the most important, but least evaluated components of natural stream channel design in bedrock dominated channels, alluvial channels, colluvial channels, and wood-controlled channels alike. As a design component, sediment transport analyses focus on providing for sediment continuity, a factor that is repeatedly cited as a condition for true channel stability.[11] Channel stability in this context implies that there is no net aggradation or degradation of the channel bed, or more simply, that rates of sediment erosion and deposition are in approximate dynamic balance.[12]

Sediment transport analysis poses many challenges. Most sediment transport analyses and design methods focus on channel competence, or the capability of a channel to transport bed material of a given size. Just as important as competence, but less frequently addressed, is consideration of the volume (capacity) of sediment that a channel is capable of transporting. Measurement and prediction of sediment mobility and transport volumes are notoriously difficult and, in most cases, inaccuracies can be by orders of magnitude.[13] Regression equations based on sufficient sampled data provides the most accurate rating curves of sediment discharge to stream flow. Whenever possible, sediment sampling data should be used to calibrate or aid in selection of transport equations. Model results tend to be more reliable as a comparative tool for “before” and “after” conditions rather than in determining absolute values. For this reason, analysis results should, in general, be used comparatively rather than absolutely. A number of currently accepted sediment transport analysis approaches and techniques are presented below.

2.2 Estimating Sediment Size

Sediment transport evaluations generally begin with a determination of the size fractions of sediment present within a given reach of channel. The measurement of sediment caliber can be performed by several methods including pebble counts, sieve analyses, or suspended sediment measurements. The most commonly used method of sampling coarse riverbed material is that developed by Wolman.[14] Despite the development of more sophisticated statistical techniques for bed material analysis, the pebble count method remains widely used due to its simplicity and almost universal acceptance.[15] Pebble counts are based on analysis of the relative area covered by given sizes, and essentially consist of measuring the intermediate axis of 100 (or, better, up to 400) individual sediment particles collected either at random or within a grid[16]. This sample represents the armor layer, and the resulting particle size distribution will generally be coarser than the average bed material distribution.

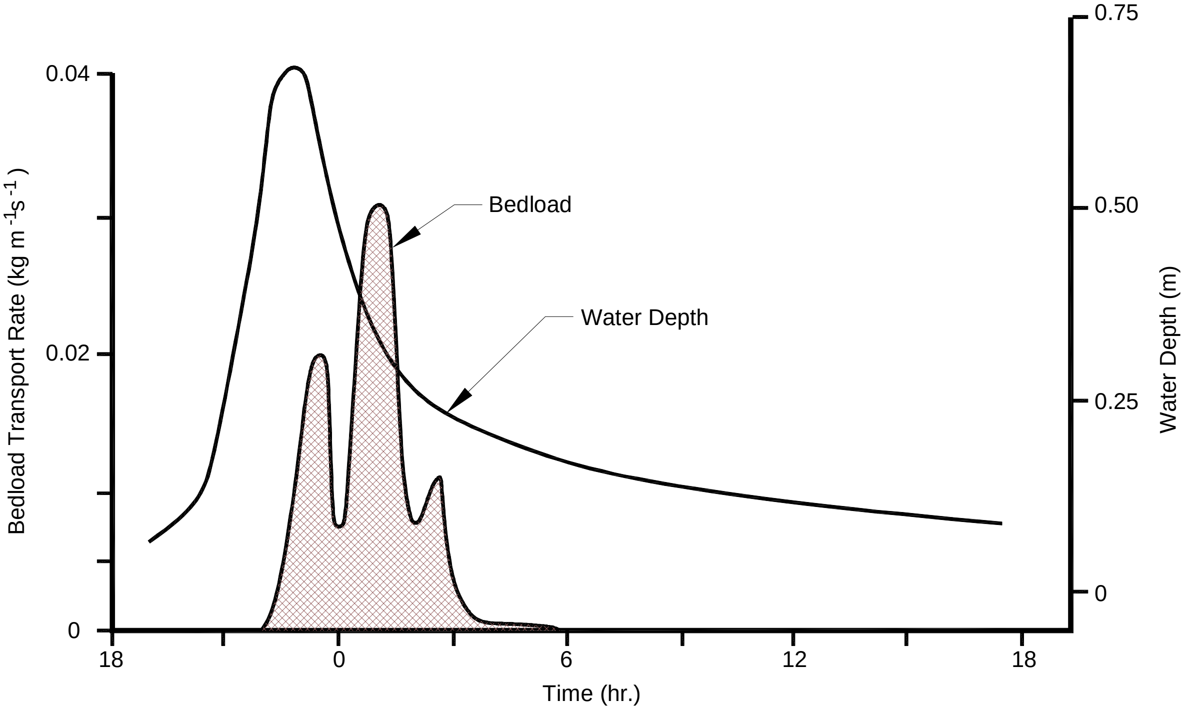
Note that some authorities do not recommend pebble count sampling for sediment transport computations[17],[18]. Pebble counts tend to be biased towards larger particle sizes, and as such are well suited to hydraulic roughness determination, but underestimate the presence of smaller size fractions, which can make up an appreciable portion of the bedload even in gravel-bed streams.

This is due to a "hiding factor" effect, whereby small particles lodge in crevices smaller than the fingertip, and due to a psychological tendency to chose a larger, more palpable particle during the sampling process.

To avoid this bias, volumetric sampling with sieve analysis is necessary. The "barrel sampler" method is a standard volumetric sampling technique,[19]. Sieve analysis is conducted on bulk samples taken from the field, and consists of sifting sediment through several standard sized sieves[20]. The amount of sediment remaining on each sieve is then weighed to determine the percent of the total weight of a given size fraction. It is best to sample the armor or surface layer separately from the subsurface rather than mixing the two during volumetric sampling, as some transport models require one or the other. Volumetric sampling will always be necessary in cases where the dominant bed material is sand or finer. When the material is very fine, suspended sediment measurements are necessary. Suspended sediment measurement is usually done by pipette analysis[21]. Sediment sampling allows for estimation of size gradations in motion at given flows and provides useful information on design elements relative to substrate size.

2.3 Bedload Movement

Sediment in fluvial systems tends to move in a series of slugs, pulses, or waves[22],[23].



Generally, the coarser the sediment the more infrequent and concentrated in time the movement is. For example, in a study on the East Fork River in Wyoming, Meade[24] concluded that sediment moved in three pulses over a one-year period. The movement of each pulse was correlated with the pulse of water discharge resulting from snowmelt. This study also suggested that sediment is transported downstream in a series of waves; when discharge increases, material stored in riffles moves to the next riffle downstream. Such wave-like or pulse-like movement is typical of semi-arid streams (or streams with coarse bed-load) and it may be less common in humid environments.

2.4 Incipient Mobility of Sediment

The assessment of sediment mobility within a channel requires an understanding of the sediment size gradation present, as well as the transport energy available to mobilize that gradation. In many cases, the evaluation of the transport energy available to transport the size fraction present is deemed sufficient for channel design[25]. This is referred to as "incipient mobility", and addresses mobility purely in terms of sediment size mobilized, rather than sediment volume mobilized. In more complex cases, however, such as those in which the incoming sediment volumes are either excessively large or small, the more difficult calculation of transport volumes may be necessary. Sediment volume is typically a function of stream power, which represents the energy needed to transport sediment in a channel, or, equivalently, a function of hydraulic shear stress, which refers to the force on the streambed. Stream power is a representation of channel capacity, or the quantity of material that the flow is able to transport. A thorough review of various stream power equations is provided by Rhoades[26].

The coarse fraction of a given sediment gradation is generally not in motion under low flow conditions. As flow increases, the energy imparted on sediment increases until at some point, the particle is mobilized. The point at which a sediment particle is just set into motion is referred to as incipient motion, and the shear stress at incipient motion is called the critical shear stress.

Shear stress is a measure of the erosive force exerted by flow on the channel boundary. Total shear stress created by flow along meandering rivers with natural topography is partitioned into shear exerted on bed, banks, bed forms, wood, vegetation, etc.[27] Shear stress exerted on bed and banks is created by water flowing parallel to the boundaries of the channel, with the force acting parallel to the area. Bank shear stress can be estimated by multiplying the average shear stress value by a coefficient (see Lane, 1955, or Chang, 1988). Maximum bank shear, based on a wide, trapezoidal channel, is approximately 0.75 times the maximum bed shear at a distance 1/3 up from the channel bed. Different channel shapes and bends will also affect the values for bank shear. A more thorough discussion of shear and methods to calculate shear is provided in the *Hydraulics Appendix*.

Shear stress calculations determine the force of the water on the channel particles. By knowing the amount of shear stress in a stream, the particle size necessary to withstand these forces can be found. This is important when designing a channel to withstand a certain design flow or flood flow. Average shear stress is calculated by the equation,

$$\tau = \gamma R s$$

where τ is the shear stress, γ is the specific weight of water (specific weight of water is inversely related to water temperature), R is the hydraulic radius (R = cross-sectional area of flow divided by the wetted perimeter), and s is the slope of the channel. For wide shallow channels with width/depth ratios of 12 or higher, channel depth can be substituted in place of hydraulic radius to simplify the equation shown above. Shear stress is commonly expressed in units of pounds per square feet (psf). The water depth is a function of flow magnitude and channel geometry.

Shear stress will therefore be greatest in steep streams during high flows.

Critical shear is the shear stress required to mobilize sediment of a particular grain size. In order to calculate critical shear stress, the Shields equation is used:

$$\tau_c = \tau_c^{*}(\gamma_s-\gamma)D$$

where τ_c^{*} is the dimensionless Shields parameter for entrainment of a sediment particle of size D, and γ_s and γ are the unit weights of sediment and water, respectively, expressed in pounds per cubic foot. Generally, the parameter D is taken to be D_{50}, the median grain size of the bed sediment, and, dimensionally, must be in units of feet. The Shields parameter is dependent on particle size and packing, and may range from 0.01 for loosely packed gravel to 0.1 for imbricated deposits (imbricated deposits have been arranged in a shingled fashion by stream flows and are particularly difficult to mobilize). Incipient mobility of stream sediments has been actively researched for over 80 years, and a summary of this research can be found in Buffington and Montgomery, 1997[28]. Their work suggests that the lack of universal Shields parameter values warrants great care in selecting those values in mobility assessments.

In incipient mobility assessments, the critical shear value is generally calculated using the D_{50} of the sediment gradation present. The use of the D_{50} to characterize the bed material size in mobility analysis is based on the hypothesis of equal mobility[29]. Originally proposed by Parker et al, (1982), this hypothesis assumes that the "*bed-load* size distribution is approximated by that of the *substrate* for all flows capable of mobilizing most available gravel sizes" (emphasis added). Note also that "substrate" here refers to the subsurface[30], which is another case for determining D_{50} with volumetric sampling (see above). Although a number of authors have argued that bed-load size characteristics change in a phased or continuous manner in relation to discharge, the equal mobility hypothesis is still widely used in incipient motion analysis[31],[32],[33]. This is probably due to the added level of complexity, and perhaps uncertainty, involved in analyses that allow for bed-load size characteristics to vary with discharge.

A perhaps more significant aspect of the equal mobility hypothesis is its relation to the dynamic pavement concept of Parker et al. for gravel bed streams,[34]. In this view, the coarsened surface layer (termed "pavement," rather than armor, to distinguish it from immobile surface layers) persists at all flows, even though all available particle sizes are present in the bedload. The surface coarsening "hides" smaller particles from the flow, thus rendering them less mobile, while coarser particles project into the flow. Thus, the critical shear stress for smaller and larger particles tend to "equalize." The net result is equilibrium between the bed material and the bed load, which allows the stream to transport the coarse portions of its bedload supply at the same rate as its fine portions. This "hiding factor" has been expressed mathematically, and can be used to predict critical shear stress of any particle size from that of the D_{50} size, and to estimate the D_{50} critical shear stress from the ratio of pavement to subsurface D_{50}[35].

Sediment mobility has been described in terms of shear stress ratio, which (adopting the equal mobility hypothesis) is the ratio of the shear stress present to the critical shear required to mobilize the D_{50}. Wilcock and MacArdell[36] estimated that a shear stress ratio of 2 is needed to mobilize the entire bed of a channel (although this depends to some extent on the particle size distribution). Channel stability was defined by a bankfull shear stress ratio of 1 in the assessment procedure developed by Johnson et al.[37]. This implies that under conditions of sediment transport equilibrium, the median grain size is at incipient mobility at bankfull discharge. Furthermore, at a bankfull shear stress ratio of greater than one, the channel is likely to degrade; if the ratio is less than one, transport is limited and aggradation is likely. Many practitioners consider incipient motion for the D_{84} at bankfull as a "rule-of-thumb" design parameter [38]. Channel design allowing incipient motion for the D_{50} may result in channels that aggrade over time. Other practitioners use incipient motion for the D_{100}, the largest alluvial particle, as a target design criterion[39].

2.5 Channel Competence-Based Methods of Sediment Transport Analysis

Incipient motion analyses can be used to assess channel competence and to design channel components (including habitat structures constructed with rock) to be stable under a given discharge. USDOT, 1988[40] is a useful reference for utilizing tractive force (shear stress) analysis for design. Shear stress is not, however, a practical measure of tractive force in steeper channels, because a large proportion of the shear stress is manifested as form resistance (turbulence around large objects) rather than particle resistance (frictional drag on bed particles)[41].

2.5.1 Tractive Force Analysis

Analysis of tractive force, a generalized measure of shear stress, can be used to determine channel geometry (considering primarily depth) based on the mobility of bed sediment[42]. Using this approach, incipient motion analysis as described in "Incipient Mobility of Sediment" (above) is used to assess the mobility of the streambed and bank materials. Because the theoretical mobile particle size is calculated, the tractive force method can be used to design a channel that is essentially rigid (non-erodible) at the design discharge. Tractive force analyses can also be used to design channel components, such as banks, to withstand the shear forces associated with a given design discharge. USDOT, 1888 includes information on the calculation of shear in-channel bends and on the shear resistance of various materials commonly used in channel design. A summary of these calculations and materials is provided in the *Hydraulics Appendix*. Alternatively, if a mobile channel bed is desired, tractive force analysis can be applied to determine a fraction of the bed material that is mobile at a given design discharge. Two methods for addressing mobile channel beds in design are addressed below.

2.5.2 Mobile Channel Bed Under Fixed Slope Conditions

This approach can be applied when slope is fixed due to vertical constraints as well as lateral floodplain constraints. Analysis of moving (or 'live') beds with a known or constrained slope most often makes use of extremal hypotheses. Extremal hypotheses state that a stable channel will adopt dimensions that lead to minimization and maximization of certain parameters. For instance, extremal hypotheses include the minimization of stream power, maximization of sediment transport, minimization of stream power per unit bed area, minimization of Froude number, and the maximization of friction factor. These hypotheses and their application to river design are summarized in Chang, 1988. Chang combined several of the extremal hypotheses, along with standard hydraulic analysis, to generate a numerical model of flow and sediment transport, the FLUVIAL 12 model. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield channel depth and width when given discharge, slope, and bed material size.

2.5.3 Mobile Channel Bed Under Known Sediment Concentration

Using this approach, design will ensure that the sediment entering the reach is transported out of the reach by manipulating channel dimensions. Upstream stable channel dimensions can be used to calculate an assumed sediment supply. Channel designs will be iterated such that the channel dimensions are all capable of transporting the incoming sediment load. Because many combinations of channel dimensions will be able to do this, families of slope-width or slope-depth relations are the end result of this type of analysis. The designer then selects any combination of channel properties that are represented by a point on the curves. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth. The hydraulic design package ‘SAM’ performs this series of analyses for alluvial channels and is available for public use[43].

2.6 Limitations of Competence-Based Methods

Sediment size and incipient motion particle size are relatively easy to characterize from deposited bed sediments and hydraulic analysis (see the discussion of “tractive force” above). However, as previously mentioned, sediment volume is much more difficult to quantify. Sediment volume is typically calculated using sediment transport equations, which are notoriously inaccurate. There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. As such, they are only applicable to specific types of channels.

Modeling of sediment transport remains one of the central thrusts of fluvial geomorphic and hydraulic research. It is likely that quantification of sediment volume will eventually become a routine part of channel design once the limitations of sampling and characterization are reduced. Presently, however, the scope of many project design efforts does not include an analysis of sediment transport volume, and quantifying sediment transport remains one of the greatest challenges of, and limitations to, river channel design.

3 SEDIMENT TRANSPORT EQUATIONS AND MODELS

There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. **Table G2** lists a number of transport equations and the slope and sediment sizes for which they were developed. The applicability of most of the equations is related to the local bed particle size. Whenever possible, the use of measured sediment loads for testing and calibration of the chosen equation(s) is preferred. Actual equations and detailed descriptions are available in standard sediment transport texts, (e.g., Chang).

Table G2. Commonly used transport equations and the conditions for which they were developed

Equation Name	*Year*	*Slope Range*	*Sediment Size*	*Data Source*	*Notes*
Meyer-Peter Muller[44],[45]	1948	0.0004-0.02ft/ft	s.g = 1.25-4 Dm = 0.4mm - 30mm Distributions ranged from graded to sorted sediments	Flume tests: 15cm-2m wide 1cm-120cm deep no bed forms	Gravel bedload; Assumes unequal mobility, no hiding factor, thus not well suited to paved or armored beds
Toffaleti[46]	1969	n/a	River data: Ds = fine and medium sand (0.125-0.5mm) Flume data: Ds = 0.3-0.93mm	Based on data from seven rivers: 1ft-50ft deep; and, flume data from four investigators: 10.5in-8ft wide by 2in-2ft deep	Sand bedload in large rivers
Yang[47]	1972		0.137-7.01mm	Flume and field data, 0.037 to 49.9ft deep, but rarely exceed 3ft depth.	Total load; Sand bed
Parker et al.[17],[34]	1982	0.00035-0.0108	Pavement 44-76 mm; Subsurface 18-28 mm	Five rivers: Width 5-198 m, Depth 0.31-6.4 m, Discharge 1.16-3500 m^3/s	Gravel bedload; Incorporates equal mobility, hiding factor
Ackers and White[48]	1973	N/a	Uniform sediments Ds > 0.04mm Ds < 28.1mm	Flume: depth < 0.4m Fr < 0.8	Total load
Engelund and Hansen[44]	1967		Dm = 0.19mm, 0.27mm, 0.45mm, 0.93mm. Geometric std dev – 1.3, 1.6 Application limits: Dm>0.15mm s.d. (Ds) < 2	Based on four flumes: 8-ft wide by 150-ft long) tests by Guy et al.[49]	Total load; Sand bed w/ dunes
Laursen[50]	1958	0.00043-0.00210	s.g. ~ 2.65 Dm = 0.011mm – 4.08mm Distributions ranged	Based on various flume tests by others: Flumes ranged from: 10.5in wide x 40ft	

			from well sorted to well graded	long to Laursen’s 3ft wide x 90ft long Also compared results to three small streams: 0.12-1.3ft deep Dm = 0.277, 0.86, 0.287mm With good to fair results.	
Wilcock et al.[51],[52],[31]	2002		Sand-gravel mixtures, with sand (<2 mm), in proportions from 6-59%. Flume studies: Surface 2.6 – 17 mm Subsurf. 5.3-12.2 mm Rivers: Surface 12 – 53 mm Subsurf. 1.2 – 20 mm	Flume studies and four gravel-bed rivers	Gravel bed rivers, using two-fraction (sand/gravel) bedload model

Another approach, which yields greatly improved accuracy with little increase in modeling complexity, is to use a site-calibrated sediment transport model[18],[52],[53]. Here, one of the above models, such as Parker et al.[18], is calibrated to one or more bedload measurements from the site under study using a statistical optimization procedure. Errors due to differences between actual site characteristics or physical measurement techniques and those used in model development tend to calibrate out. Standard procedures for bedload sampling are available[54]. Although bedload sampling is somewhat time consuming, the sampling and calibration procedure is much less costly for the improved accuracy than the more-elaborate 2-D or 3-D modeling discussed below.

In addition to the specific sediment transport equations, there are several sediment transport numerical models available for use in river engineering applications. The most common approach to sediment transport modeling is a steady state, one-dimensional approach. That is, using channel dimensions, flow conditions, and sediment characteristics, the model performs hydraulic calculations, and then using these hydraulic characteristics, calculates sediment loads for each of the channel reaches. Based on the quantity of sediment transported for the given flow, the channel elevation (i.e., slope) is adjusted via a routing scheme. The program either performs calculations for a given range of flows, or for a given flow, the model continues until there are no more channel adjustments (i.e., equilibrium conditions). This modeling approach is the basis for the Corps of Engineers HEC-6 model[55], and is widely used. The primary limitation of the HEC-6 approach is that it is a one-dimensional model. There are a number of inherent assumptions including: steady, uniform flow and rigid boundaries with no changes allowed in the channel width and no lateral migration.

The next level of modeling is the semi two-dimensional modeling approach. In two-dimensional models, a similar coupled hydraulic and sediment routing scheme is used, but at the end of the routing run an estimate is made as to whether or not channel width adjustments are appropriate. Several methods are used to estimate stable channel widths: extremal hypotheses as described earlier (GSTARS 2.0, FLUVIAL 12)[27], or bank stability estimated from stable slope angles (GSTARS 2.0, CONCEPTS)[27]. These models add a significant feature of width adjustment without adding significantly to data or analysis efforts needed. In all, these are felt to be the most appropriate approaches for most river restoration designs, particularly those projects that will involve significant modification to channel alignment, slope, or sediment loads.

The third level of modeling is the fully two-dimensional or three-dimensional modeling approaches. These models represent significant improvements in describing fluvial erosion and hydraulic processes, but this comes at a significant increase in the level of effort needed both in terms of data and analysis requirements beyond current capability. In fact, while utilization of 2-D modeling is beginning to become more widespread for large projects, application of 3-D modeling continues to be impractical due to technological limits such as computer capabilities and high input requirements.

4 SEDIMENT STORAGE

It is important for the channel designer to consider accommodating sediment storage within reaches. Designing a channel that transports all sediment inputs in a natural manner will, theoretically, prevent channel destabilization by excessive erosion or deposition. It does not, however, guarantee that the geomorphic and habitat benefits of sediment storage (e.g., as gravel bars) will be realized. On reaches where some degree of sediment storage is desired and appropriate, channel dimensions, planform, and roughness elements such as large wood should be varied to encourage and accommodate depositional features such as bars.

The appropriate volume/extent of sediment storage is best determined using an analog (reference) reach. Natural channels typically contain reaches characterized by deposition, transport, or relatively balanced sediment transport. Factors such as channel gradient, valley width, and wood presence/density in particular influence sediment storage on any given reach. Channel designers should take these factors into account and intentionally make provisions for sediment storage on reaches where such storage is appropriate.

5 ADDITIONAL READING

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