JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
AUGUST AMERICAN WATER RESOURCES ASSOCIATION 2005

SEDIMENT TRANSPORT AND CHANNEL MORPHOLOGY OF SMALL, FORESTED STREAMS[1]

Marwan A. Hassan, Michael Church, Thomas E. Lisle, Francesco Brardinoni, Lee Benda, and Gordon E. Grant[2]

ABSTRACT: This paper reviews sediment transport and channel morphology in small, forested streams in the Pacific Northwest region of North America to assess current knowledge of channel stability and morphology relevant to riparian management practices around small streams. Small channels are defined as ones in which morphology and hydraulics may be significantly influenced by individual clasts or wood materials in the channel. Such channels are headwater channels in close proximity to sediment sources, so they reflect a mix of hillslope and channel processes. Sediment inputs are derived directly from adjacent hillslopes and from the channel banks. Morphologically significant sediments move mainly as bed load, mainly at low intensity, and there is no standard method for measurement. The larger clastic and woody elements in the channel form persistent structures that trap significant volumes of sediment, reducing sediment transport in the short term and substantially increasing channel stability. The presence of such structures makes modeling of sediment flux in these channels – a potential substitute for measurement – difficult. Channel morphology is discussed, with some emphasis on wood related features. The problem of classifying small channels is reviewed, and it is recognized that useful classifications are purpose oriented. Reach scale and channel unit scale morphologies are categorized. A "disturbance cascade" is introduced to focus attention on sediment transfers through the slope channel system and to identify management practices that affect sediment dynamics and consequent channel morphology. Gaps in knowledge, errors, and uncertainties have been identified for future research.
(KEY TERMS: streams; sediment transport; fluvial processes; geomorphology.)

Hassan, Marwan A., Michael Church, Thomas E. Lisle, Francesco Brardinoni, Lee Benda, and Gordon E. Grant, 2005. Sediment Transport and Channel Morphology of Small, Forested Streams. Journal of the American Water Resources Association (JAWRA) 41(4):853-876.

INTRODUCTION

Forests significantly influence channel morphology and processes in streams. Particular effects are created by within channel accumulation of large woody debris (LWD) and by channel margin trees. Wood is critically important in regulating sediment transport and diversifying channel form, thereby also having major effects on aquatic and riparian ecology (e.g., Bisson *et al.,* 1981; Sullivan, 1986; Bilby and Bisson, 1998). This paper presents a review of small forested stream dynamics, drawing primarily from research conducted in the Pacific Northwest region of North America.

Wood has its greatest effect in channels with dimensions similar to those of the larger wood pieces, hence smaller streams rather than large rivers are most especially affected. Church (1992) characterized "small channels" as ones in which individual bed particles greatly influence channel morphology. On steeper gradients, step pool is a dominant bed form. Absolute width would normally be less than 3 to 5 m. He characterized "intermediate channels" as ones with width much greater than characteristic grain size that might still be influenced by blockage across most or all of the cross-section, most often by fallen woody debris. In forests, this might include channels up to 20 or 30 m in width. Particle accumulations greatly influence channel morphology, pool riffle being a typical bed form feature. According to the British Columbia channel classification (British Columbia

[1]Paper No. 04072 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2005). **Discussions are open until February 1, 2006.**

[2]Respectively, Assistant Professor (Hassan) and Professor (Church), Department of Geography, University of British Columbia, Vancouver, B.C., Canada V6T 1Z2; Research Hydrologist, USDA Forest Service, Southwest Research Station, Redwood Sciences Laboratory, Arcata, California 95521; Graduate Student, Department of Geography, University of British Columbia, Vancouver, B.C., Canada V6T 1Z2; Research Scientist, Earth System Institute, 310 North Mt. Shasta Blvd., Suite 6, Mt. Shasta, California 96067-2230; and USDA Forest Service, Pacific NW Research Station, 3200 SW Jefferson Way, Corvallis, Oregon 97331 (E-Mail/Hassan: mhassan@geog.ubc.ca).

Ministry of Forests, 1996a,b), small and intermediate channels have a range of particle size/width ratio between 0.002 and 1.0, while relative roughness (particle size/depth) ranges from 0.1 to 1.6. Such channels are strongly influenced by the entry of wood into them. In contrast, large channels, with major bar development, meander-bend pools, and crossover riffles, are essentially hydraulically controlled, although significant wood accumulations might still occur on bar surfaces.

Whereas external sediment inputs such as mass wasting and bank collapse, along with wood accumulation, tend to dominate channel morphology – hence ecology – in small forest streams, larger channels are primarily affected by downstream fluvial sediment transport and bank erosion. "Small streams," as discussed in this paper, would be classified as small or intermediate in the channel typology of Church (1992). His definitions are relative because sediment texture and forest morphology influence the size range of such channels in a particular environment. Insofar as they speak to process, they seem more appropriate than arbitrary classifications by absolute size.

The focus on small streams stems from recognition that these represent a distinct class of streams with distinctive morphologies, processes, and dynamics. There are, of course, small, low gradient channels present in a range of environments, from mountain meadows to lowland tributaries and secondary channels. Although important geomorphic and ecologic environments in their own right, these channels are not considered here. The focus of this paper is the steeper portions of the channel network where episodic sediment and wood inputs from adjacent slopes exert significant control on channel dynamics and morphology. In these channels significant amounts of LWD tend to control the amount of sediment stored within the channel and impact their stability (e.g., Swanson *et al.,* 1982c; Bilby and Ward, 1989).

The concentration of wood in the channel decreases with increasing stream order and channel width, implying little impact of wood on channel morphology of high order streams (higher than fifth order) (e.g., Swanson *et al.,* 1982c; Bilby and Ward, 1989). On the other hand, wood typically spans the smallest streams and has little hydraulic effect there. Consequently, attention will be focused on channels that are typically of third through fifth orders (as determined in the field), which are likely to contain significant amounts of wood.

The primary objective is to critically assess channel processes relevant to riparian management around steep, wood loaded streams and to identify gaps in knowledge. Most research has been focused on large and intermediate size channels of higher order. Due to the limited available information on small forested streams, certain information accumulated from larger mountain rivers will be included in this paper, and its applicability to small streams will be assessed.

First, the fundamental phenomenon of sediment transport is considered under the headings sources, mobilization, phases of transport, measurement, variability of transport, and modeling. Then channel morphology – the product of sediment transport and deposition – is introduced under the headings reach morphology, channel units, and channel classification. Finally, slope channel interactions and disturbance are considered, with some emphasis on timber harvesting and roads.

SEDIMENT TRANSPORT

Much research has been conducted into sediment transport processes and sediment transport rate prediction in rivers, mostly in relatively large rivers. Techniques conventionally used to calculate sediment transport in large rivers are not appropriate for headwater streams where episodic sediment supply from adjacent slopes, rather than the hydraulic conditions, dominates the sediment transport regime. LWD often constitutes a significant portion of material transported by forested streams (Bilby, 1981) and is a major impediment to the downstream progress of clastic material (e.g., Megahan, 1982; Rice and Church, 1996; Hogan *et al.,* 1998).

The particulate sediment load of a stream is conventionally divided into suspended load – particles moving in the water column with their submerged weight supported by upwardly directed turbulent currents – and bed load – particles moving in contact with the bed. This division reflects the mechanics of movement and the conventional methods for measurement. A somewhat different division provides insight into channel formation and stability. Wash material is relatively fine material that moves directly through a reach without being deposited in the main channel, whereas bed material is the coarser material that is apt to be deposited and form the channel bed and banks. Wash material moves in suspension and is an important determinant of water quality; bed material may move either way. The movement of bed material along small channels will be the focus of this part of the review since that is what determines channel morphology (see Gomi *et al.,* 2005, for a discussion of fine sediment dynamics). In headwater and mountain streams there is high correspondence between bed material and bed load. Hence, bed load will be considered.

Sediment Sources

Sediment is supplied to channels from surface erosion on slopes, mass wasting, stream banks, and tributaries. In small forested streams, where the channel usually is not bordered by a valley flat or well developed floodplain, rapid mass wasting and bank erosion are primary sources of sediment supply. Roberts and Church (1986; see also Church and Ryder, 2001) summarized sediment mobilization and yield from hillslopes in the Pacific Northwest in relation to forest practices (Table 1). They reported that episodic mass wasting provides the most significant input to channels while continually recurring processes such as surface erosion and soil creep are of relatively minor importance. Ditches, roads, and skid track surfaces are the main sources of fine sediment in harvested basins in the Pacific Northwest (e.g., O'Loughlin, 1972; Swanson *et al.,* 1982c; Grant and Wolff, 1991; Montgomery, 1994, Megahan and Ketcheson, 1996). Table 2 summarizes sediment yield from episodic sources and delivery to channels for several harvested basins in British Columbia.

Sediment entering stream channels from adjacent slopes or upstream tributaries may be deposited immediately, to be remobilized and moved onward by fluvial processes at a later stage (Sutherland *et al.,* 2002), or it may travel along the channel for some distance and be deposited in low gradient reaches or behind obstacles to form sediment wedges. In the former case, the channel may be partially dammed for a more or less protracted period. Sometimes, part of the deposit remains for a very long time to form persistent, complex channel morphology. In the latter case, on sufficiently steep gradients, the immediate onward movement of the sediment mass may take the form of a debris flow, a landslide like mass flow that typically entrains additional material from the channel bed and may scour it to bedrock (Swanston and Swanson, 1976; Miles and Kellerhals, 1981; Costa, 1984; Bovis and Dagg, 1988).

Debris flows may be relatively rare in individual channels unless there is a prolific source of sediment, but they are by no means rare in steep lands. Benda and Dunne (1987) have calculated that they constitute the dominant means by which sediment is delivered into the low order drainage system in the Pacific Northwest (see also Slaymaker, 1993). The behavior of a debris flow – in particular, how far it goes – depends on the fluid/debris mixture and on total momentum (hence size of the flow). Fine sediments hold water and can flow out onto quite low gradients, whereas sandy matrix material drains readily and tends to stop the flow on gradients of order 10° or more (Hungr *et al.,* 1984). The total volume of material moved in a debris flow depends on initial volume, the distance of travel and the volume mobilized per unit length, which may be in the range 5 to 25 m^3/m

TABLE 1. Sediment Mobilization and Yield From Hillside Slopes.

Process	Mobilization Rate: Forested Slopes	Mobilization Rate: Cleared Slopes	Yield Rate to Stream Channels: Forested Slopes	Yield Rate to Stream Channels: Cleared Slopes
NORMAL REGIME				
Soil Creep (including animal effects)	1 $m^3/km/yr$*	2x	1 $m^3/km/yr$*	2x
Deep Seated Creep	10 $m^3/km/yr$*	1x	10 $m^3/km/yr$*	1x
Tree Throw	1 $m^3/km/yr$	–	–	–
Surface Erosion: Forest Floor	< 10 $m^3/km^2/yr$		<1 $m^3/km^2/yr$	
Surface Erosion: Landslide Scars, Gully Walls	> 10^3 $m^3/km/yr$ (road area only)	1x	>10^3 $m^3/km^2/yr$	1x
Surface Erosion: Active Road Surface	–	10^4 $m^3/km^2/yr$ (road area only)	–	10^4 $m^3/km^2/yr$ (road area only)
EPISODIC EVENTS				
Debris Slides	10^2 $m^3/km^3/yr$	2-100x	to $10^3/m^3/km^2/yr$	to 50x
Rock Failures (fall, slide)	No consistent data: not specifically associated with land use			

*These results reported as m^3/km channel bank. All other results reported as m^3/km^2 drainage area. Results are generalized to order of magnitude from a table that originally appeared in Roberts and Church (1986).

TABLE 2. Sediment Yield and Delivery to Channels in Several British Columbia Basins.

Location	Area (km^2)	Percent Logged	Sediment Delivery To	No. of Slope Failures		Yield ($m^3/km^2/yr$)		Acceleration
				Natural	Logged	Natural	Logged	
Chapman Creek (API)	56.0	36.3	Permanent Streams	9	45	15.9	153.9	10x
			Gullies	5	65	1.9	150.5	79x
			Unchannelled Slopes	2	54	1.9	66.9	35x
Centre Creek (API)	38.0	28.2	Permanent Streams	4	18	18.5	451.6	24x
			Gullies	21	30	53.6	293.9	5x
			Unchanneled Slopes	4	21	3.9	151.6	39x
Nesakwatch Creek (API)	48	10.1	Permanent Streams	5	28	3.6	496.3	138x
			Gullies	19	68	32.5	1,096.5	34x
			Unchanneled Slopes	8	25	7.4	454.1	61x
Howe Sound (API)	26.8	25	Permanent Streams	48	43	65.6	920.6	14x
			Gullies	6	22	5.3	254.6	48x
			Unchanneled Slopes	2	40	7	327.3	47x
San Juan River[1] (API)	517	25	Permanent Streams	83	246	20.8	247.2	12x
			Gullies	39	115	3.6	61.6	17x
			Unchanneled Slopes	12	91	1.3	74	57x
Capilano River[2] (API and ground checking)	12.9	27.9	Permanent Streams	69	25	175.8	102	0.6x
			Gullies	35	20	22.9	59.3	3x
			Unchanneled Slopes	9	13	3.7	133.7	36x
Queen Charlotte Islands[3] (API)	350	13.4	Permanent Streams	264	119	60	2,760	46x
			Gully Connected	309	150	21	370	18x
			Unchanneled Slopes	543	411	79	2,690	34x

Notes: API = Air photo interpretation.
[1]Modified from Rood (1984).
[2]Modified from Brardinoni *et al.* (2003).
[3]Northwest Hydraulic Consultants (1997, unpublished report).

(Hungr *et al.,* 1984; Fannin and Rollerson, 1993; Bovis *et al.,* 1998). Typically, only a few hundred cubic meters are involved in initial mobilization, but flows commonly grow to volumes of order 10^3 to 10^5 m^3.

Sediment from the stream bank is also entrained by water. In forested streams, roots provide strength to the bank so that bank material is much more susceptible to erosion below the rooting zone (e.g., Hickin, 1984). In boreal and temperate coniferous forests, even quite small streams (depth approximately 1 m) may scour below laterally spreading root systems. LWD positioned along banks can reduce bank erosion whereas diagonally oriented LWD may increase erosion by diverting flow toward a bank section (Keller and Swanson, 1979).

The response of a channel to external sediment supply depends on flood history (i.e., magnitude and sequence) and the sediment supply history. The temporal and spatial variation in the amount of within-channel sediment storage depends significantly on the supply from external sources (e.g., Swanson *et al.,* 1982a; Benda, 1990). Consequently, flow events of the same magnitude may create different channel morphologies and sediment mobility (e.g., Buffington and Montgomery, 1999; Lisle *et al.,* 2001). Ryan (2001) compared three streams which differ in rate of sediment supply and consequent channel morphology. Streams with a relatively large sediment supply have typically fine surface sediments and high sediment transport rates. In creeks with low sediment supply, the sediment transport rates are relatively low and the bed surface is well structured and typically coarse-textured (Ryan, 2001), consistent with experimental findings of Parker *et al.* (1982), Dietrich *et al.* (1989), and Hassan and Church (2000).

Internal sources of sediment supply occur within the stream channel. Bed material is entrained from sediment stored in pools or behind obstructions such as logs and boulders, including rarely moved clastic keystones and pieces of LWD (e.g., Whittaker, 1987; Lisle and Hilton, 1992). Mobilization may result from the displacement of the obstruction, suddenly releasing large volumes of sediment (Sidle, 1988; Smith *et al.,* 1993a, 1993b). The localized release of large sediment stores results in the movement of sediment in waves or pulses. Swanson *et al.* (1982a,b) and Megahan (1982) noted that the volume of temporarily stored material is usually more than 10 times the average annual export of total particulate sediment. Thus changes in sediment storage can cause major changes in sediment yield even if there are no external sources. On the other hand, within channel sediment storage also delays and attenuates sediment waves introduced from external sources. Within channel storage of sediment can produce an event-scale hysteresis effect on transport, the sense and magnitude of the hysteresis loop depending on the amount of stored sediment and position along the channel (Meade, 1985) and the timing of sediment mobilization within the event.

Initiation of Motion

An outstanding characteristic of small channels is the high boundary roughness created both by the large clasts and by the frequent obstructions and rough banks that make up the boundary. This extracts much energy that might otherwise be available to mobilize bed material. The force exerted on the grains may be a small fraction of the total force exerted by the flow. The standard approach to predict sediment transport in stream channels is to suppose that an unrestricted supply of material is available in the channel, and that it is moved in quantities that are fundamentally correlated with the forces imposed by the water flow. However, it is first necessary for the flow to pass some threshold required to entrain any material at all.

The pioneering modern investigation of the shear stress needed to initiate the movement of uniform grain sizes was by Shields (1936). On the basis of experiments with narrowly graded sediments, he determined that, for particles larger than 5 mm, the scaled shear stress (dimensionless mobility number scaled by grain size) is constant at about 0.06. This means that the dimensioned critical shear stress increases in simple proportion to grain size. Assuming that individual grain size fractions in a mixture have no influence on each other, the force needed to initiate movement of a given size would be equal to that in a uniform bed composed of that size. Larger material in narrowly graded sediments would be left behind when fine material moves away.

While Shields' equation appears to work well in fine and well sorted sediments, its application to the poorly sorted sediment typical of small forested channels has proven more difficult. Prediction of the initiating conditions for nonuniform sediment motion remains an open question requiring consideration of bed surface texture and structures.

If there is a wide range of grain sizes in the bed, the larger grains may be moved more easily because they are more exposed and the position of the pivot point about which they move is lower than that of smaller grains (e.g., Komar and Li, 1988). Correspondingly, the smaller grains may be sheltered from the flow and their movement may be obstructed by the larger ones (e.g., Parker and Klingeman, 1982). In steep streams, Shields' criterion may be modified to take into account the particle's downslope weight (e.g., Graf, 1971; Mizuyama, 1977; Rickenmann, 1990, 2001). The effect of gravity on the relative motion of small and large particles in steep channels has been examined by Solari and Parker (2000). They found that large particles are more mobile than small ones on gradients greater than about 2 percent. These phenomena tend to reduce the range of dimensioned shear stresses over which mobilization of all sizes occurs.

Still, in heterogeneous sediments, there is no single flow (or mobility number) above which all clasts of the same size will move (Wilcock and McArdell, 1993, 1997). Furthermore, bed surface structures, such as imbrications and bed forms, restrain part or all of the beds until higher forces are applied (Church *et al.,* 1998). Large parts of the bed remain stable during small and medium size events (e.g., Lauffer and Sommer, 1982) while, during large events, the bed surface structures are destroyed and the channel is freighted with a large amount of sediment (Jaeggi, 1995). In summary, for poorly sorted sediments a range of threshold mobility numbers has been reported from 0.01 to more than 0.1 (e.g., Church, 1978; Buffington and Montgomery, 1997).

Sediment mobilization in steep headwater streams is ultimately controlled by sediment supply from outside the channel and by the step pool and boulder morphology. These morphologies are controlled by the large individual grains that form stable steps or by woody debris that performs a similar role. While some of the key material is moved by running water, many of the channel morphological elements are supplied to the channel by nonfluvial processes such as debris flows and debris slides. Fluvial sediment entrainment depends upon the particle location within the highly structured (e.g., step pool) morphology. The overlap between fluvial and nonfluvial processes (e.g., Montgomery and Buffington, 1997) in controlling the bed stability makes modeling of the system difficult (see Benda and Dunne, 1997b). Therefore, the question of channel stability in these streams is still largely an open question in fluvial geomorphology that needs to be further studied.

Bed Material Transport Phases

Field studies of sediment transport in gravel bed rivers have identified two (e.g., Jackson and Beschta, 1982; Klingeman and Emmett, 1982; Andrews, 1983) or three phases (Ashworth and Ferguson, 1989; Warburton, 1992) of transport (Figure 1). In two-phase models, Phase I occurs when fine material, mainly sand, moves over a stable bed; Phase II occurs during higher flows when coarser material is entrained locally. In Ashworth and Ferguson's (1989) three-phase model of transport, Phase I consists of over passing sand; Phase II occurs during moderate flows when size selective entrainment and transport of local bed material occurs; and Phase III occurs during the highest flows under conditions of effectively equal mobility of all sizes (Parker *et al.,* 1982). Ashworth and Ferguson's Phases II and III correspond to Wilcock and McArdell's (1993, 1997) partial mobility (only some of the exposed grains in a given size range experience entrainment within a period of time) and to classical full mobility, respectively (Figure 1). In Figure 1b, the scaled fractional transport rate is computed as $q_b p_i / f_i$, where q_b is the sediment transport rate (g/m s), p_i is the proportion of each size fraction i present in the transported material, and f_i is the proportion of each size fraction in the bulk bed sediment. Distinctions are made between overpassing, partial mobility, and full mobility.

Phase I conditions cover a relatively narrow range of discharges. Gravel sizes are likely to be mobile only at the transition to and during Phase II (e.g., Andrews, 1983). In almost all places and times in forest streams, Phases I and II dominate the sediment transport regime while Phase III occurs at relatively extreme flows. In sufficiently steep channels, Phase III transport may develop into a "debris flood," a condition of very high transport in which substantially the entire bed moves (e.g., Warburton, 1992). Debris floods give rise to lobate wedges of gravel when the material is deposited. It is likely that they are restricted to intermediate gradients (< 15 degrees) since, on steep gradients (> 15 degrees), they are apt to propagate into debris flows. The essential difference between these phenomena is that, whereas the former remains essentially a fluid flow with sediment traction, the latter is a landslide like flow of a more or less homogeneous sediment-water mixture possessing distinct rheology. There is little systematic documentation of debris floods, which should be distinguished from so-called "hyperconcentrated flows." The latter entail sediment concentrations in the water column of greater than 40 percent by weight (20 percent by volume) (see Costa, 1988; Jakob and Jordan, 2001). Such unusually high suspended sediment concentrations modify the turbulent flow. Debris floods feature unusually high bed load transport in steep, coarse grained channels which may, or may not, be associated with suspended sediment hyperconcentration.

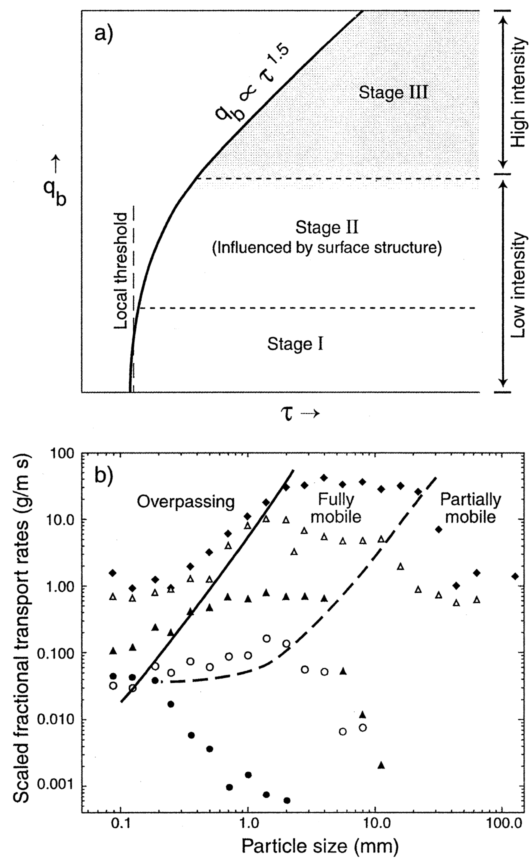

Figure 1. (a) Schematic Diagram of Sediment Transport Rate Versus Shear Stress for Varying Grain Sizes; and (b) Transport Ratio as a Function of Grain Size, a Selected Example From Harris Creek, British Columbia (after Church and Hassan, 2002, Figure 2b: p. 19-4).

In channels with strongly structured beds, the onset and duration of Phase II and Phase III transport is strongly constrained. Long term measurements of bed material yield in steep streams in Austria revealed very little sediment movement during floods and showed that the actual sediment transport rate is much lower than the theoretical (that is, functionally estimated) transport capacity (Lauffer and Sommer, 1982). Furthermore, the size distribution of the bed load material was much finer than the armor surface layer, implying that the surface remained intact during most observed floods (see Lauffer and Sommer, 1982, Figure 6, p. 442).

Recently, Zimmerman and Church (2001) identified three distinct sediment populations in a step pool channel, each exhibiting a characteristic degree of stability. The coarsest population includes the boulders that form the step keystones, which appear to be immobile under commonly recurring flows (keystones have been reported by Grant *et al.,* 1990 to be mobilized during flows with return period of 25 to 50 years). The loose cobble population in the pools appears to be mobile once every few years. There is also a granule gravel population which is found as lee side “shadow" deposits and is the most mobile sediment found in the channel. At the bankfull flow condition measured by Zimmerman and Church (2001) it appeared that the loose cobble population was on the threshold of motion. Ryan (1994), Adenlof and Wohl (1994), and Blizard and Wohl (1998) similarly found that a relatively small amount of fine material moves during a flow event and most of the channel bed remains stable. The distinct sediment populations identified by Zimmerman and Church (2001) probably can be associated with the three transport phases in such channels.

Ryan and Troendle (1996) developed rating curves for bed load transport in St. Louis Creek, a cobble boulder stream in Colorado. They then related the rating curves to bed load transport phases and flow conditions relative to bankfull discharge. Phase I (phase zero in their terminology) transport occurred at half bankfull discharge, Phase II was observed between 70 and 100 percent bankfull discharge, and it seems that Phase III is associated with flow well beyond bankfull stage (Andrews, 1984; Ryan and Troendle, 1996). Bankfull discharge in the study site occurs typically between 5 and 20 days per year (or about 1.4 to 5.5 percent of the time). These estimates concur with that of Andrews (1984), who lists a range for the bankfull discharge between 0.12 and 6.5 percent of the time for a number of streams in Colorado. The return frequency and duration for Phase III type transport are difficult to estimate but might be related to the decades length estimates of Grant *et al.* (1990) for boulder mobilization.

In summary, streambed structure and particle caliber appear to dictate the transport mechanisms of bed material within the channel. Phase III transport likely occurs only in debris floods, and sediment transport normally is restricted to Phase I even though this phase may encompass the transport of only granule gravel. With a characteristically wide spread in particle size distribution, the unavoidably selective transport results in bed load being finer – usually much finer – than the streambed surface material (e.g., Lisle, 1995).

Measurement of Bed Material Load

In forest headwater streams, measurement of bed material load is customarily considered to be equivalent to measuring bed load. Bed load measurements have been made using box or basket samplers, pit traps, and magnetic detection devices, and by observing weir ponds and tracers. Bed material transport occurs under relatively high flow conditions for a very short period of time (previous section), and therefore it is difficult to measure. This is particularly true in step-pool and boulder streams in which the operation of bed load sampling devices is difficult.

Weir ponds provide volumetric total bed material transport between surveys and particle size distribution of the integrated sample (e.g., Ryan and Troendle 1997; Gomi, 2002). Data of this nature provide a record of long-term sediment yield but the information is limited in temporal detail (Troendle *et al.,* 1996). Pit traps have been deployed successfully in small gravel bed rivers in a wide range of environments (e.g., Milhous, 1973; Hayward, 1980; Reid *et al.,* 1980; Sawada *et al.,* 1983; Kuhnle, 1992; Reid and Laronne, 1995). Traps are assumed to yield relatively good estimates of event bed load transport (Sterling and Church, 2002) and are recommended for small forested streams. However, they provide only period average or event transport rates, unless continuous weighing devices such as pressure transducers (e.g., Reid *et al.,* 1980) are installed beneath them.

Box and basket samplers provide site specific or cross-sectional averages of transport rate and sediment texture. A large number of samples are needed in order to derive an acceptable estimate of sediment transport rate, which is expensive, time-consuming, and labor intensive (e.g., Emmett, 1980; Hubbell *et al.,* 1985; Ryan and Emmett, 2002). The Helley-Smith sampler is the most commonly used, however, it was designed for use in coarse sand and granule-gravel beds (Helley and Smith, 1971) and is known to produce biased results in coarse materials (Sterling and Church, 2002).

Automatic detection systems can track the movement of natural or artificial, inserted magnetic tracers. The underlying principle is that when a magnet passes over an iron cored coil of wire, a measurable electrical pulse is generated (e.g., Ergenzinger and Custer 1983; Reid *et al.,* 1984; Bunte, 1996). This type of system provides *in situ* continuous measurements of bed load movement during flow events, and an unlimited number of stones can be recorded. A system has been developed and tested by Tunnicliffe *et al.* (2000) that promises a high resolution picture of bed load transport activity. The main advantage of these systems is the automatic detection of the traced particles, but they require relatively sophisticated data recording and analysis. There also remain difficulties to translate stone count rates into mass flux rates.

Recovered tracers can be used to estimate volumetric sediment transport, three-dimensional dispersion of sediment, and flow competence, but their deployment and recovery are labor intensive. Studies using magnetic tracers have been conducted in the Pacific Northwest, including Hassan and Church (1992, 1994), O'Connor (1994), Gottesfeld (1998), and Haschenburger and Church (1998). Hassan and Ergenzinger (2003) provide a comprehensive review of the available techniques.

Finally, scour chains have been used to estimate depth of scour and fill, depth of the active layer, and sediment mixing between the surface and the subsurface (e.g., Leopold *et al.,* 1964; Hassan, 1990; O'Connor, 1994; Montgomery *et al.,* 1996a; De Vries, 1997; Haschenburger, 1999; De Vries *et al.,* 2001). This information is directly related to bed material flux.

Box or basket type bed load samplers remain the most frequently used method because of their logistical simplicity, even in headwater streams, but there is little agreement as to what is considered to be a valid sampling scheme in any fluvial system. The best sampler for obtaining true sediment transport rates in gravel bed rivers remains undecided (Ryan and Troendle, 1996).

Variations in Sediment Transport

A number of studies have examined the short term variation in sediment transport through a flood hydrograph (cf., Williams, 1989). For a given flow, the sediment transport rate on the rising limb of the hydrograph often is higher than that on the falling limb (clockwise hysteresis) (Figure 2a) (O'Loughlin *et al.,* 1978; Paustian and Beschta, 1979). This variation is due to sediment supplied between floods that are mobilized as soon as flow increases. Counter-clockwise hysteresis (Figure 2b) occurs on a well packed and armored stream bed where little sediment moves until the armor layer is disrupted, usually near peak flow. Then, relatively large amounts of sediment move during the falling limb (Milhous, 1973; Reid *et al.,* 1985; Lisle, 1989). Gomi (2002) reported both clockwise and counter-clockwise hysteresis in bed load transport, depending on the amount of sediment stored within the channel system and the inputs from adjacent slopes and bank collapses. During a flood the bed load transport rate often peaks with or after the peak discharge (e.g., Paustian and Beschta, 1979; Reid *et al.,* 1985; Moog and Whiting, 1998). The latter authors further demonstrated clockwise variation in bed load at seasonal time scale.

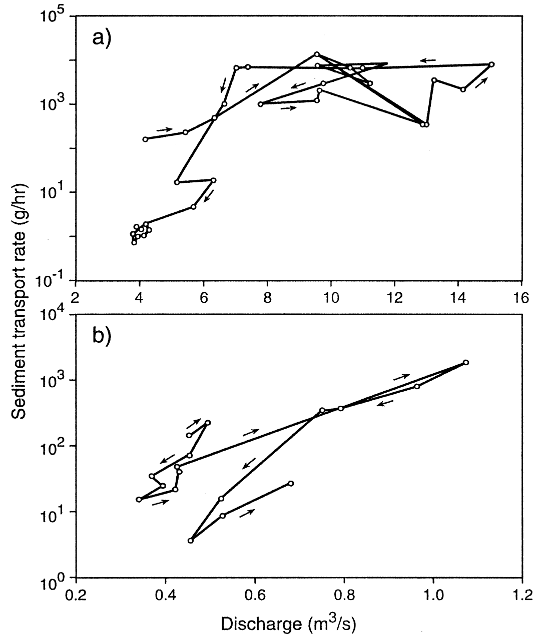

Figure 2. Time Line Plots for the Sediment Transport Rate Versus Discharge for: (a) Harris Creek (after Hassan and Church, 2001, Figure 6c, p. 819); and (b) Bridge Creek (based on Nanson, 1974, Table 2, p. 481).

In almost all reported cases, the bed load fluctuates for a given flow condition with time scale ranging from a few minutes to two or three hours, depending on the channel size (e.g., Reid *et al.,* 1985). The texture of the mobile sediment also may vary significantly during the course of a flow event (Hayward, 1980; Hassan and Church, 2001). It has been suggested that short term variations result from partial destruction of the armor layer (e.g., Milhous, 1973), the differential pattern of scour and fill in relation to channel morphology (e.g., Andrews, 1979), turbulent fluctuations in flow velocity (DeJong, 1995), the development and destruction of small scale bed forms such as pebble clusters or stone cells, and micro-scale eddies developing around obstacles (Reid *et al.,* 1985; Hassan and Reid, 1990; Hassan and Woodsmith, 2004).

Variations in the sediment transport rate over longer periods of time are associated with episodic sediment supply from slopes and banks (Gintz *et al.,* 1996; Ryan, 1997) and from sediment stored within the fluvial system behind LWD and bars (e.g., Lisle, 1986; Adenlof and Wohl, 1994). Gomi (2002) examined the influence of woody debris on sediment movement and storage in relation to timber harvesting and episodic sediment supply in headwater streams. He found that the availability of sediment and woody debris alters the threshold for sediment entrainment, transport processes, and sediment storage. Sediment supply and the abundance of woody debris are the main controls of particle travel distance. For example, a large sediment supply results in an increased distance of movement (Gomi, 2002). Rice and Church (1996) related scour depth and particle travel distance to log jam characteristics such as age, integrity, and span: old jams are likely to be more permeable than younger ones, allowing more sediment to move through. They found that tracers placed on the upstream side of young, impermeable jams remained in place whereas tracers placed on the downstream side of the jam moved for a relatively short distance. In the case of old, permeable jams, most of the upstream tracers moved and surpassed those placed on the downstream side of the jam. These results strongly suggest that jam conditions exert significant influence on sediment mobility.

A number of studies have linked temporal variations in sediment transport to secular variations in sediment supply from outside the channel system (e.g., Dietrich *et al.,* 1989; Ryan, 2001). Mass wasting inputs triggered by large storms or caused by forest practices or fire increase the sediment supply to channels. In streams where the transport capacity exceeds normal sediment supply, little sediment is stored within the channel so sediment transport is directly linked to episodic mass wasting inputs (e.g., Nanson, 1974). Major sediment supplies due to mass wasting may have a long term influence on both sediment transport and channel morphology.

There is evidence that episodic, rapid wedge deposition and relatively slow fluvial erosion operate cyclically with time scales ranging from decades to centuries (Pearce and Watson, 1983; Benda, 1990). This may be the case after mass wasting events associated with timber harvesting (e.g., Megahan, 1982; Wohl *et al.,* 1993; Madej and Ozaki, 1996; Benda and Dunne, 1997a) or fire (Swanson, 1981; Meyer *et al.,* 1992; Benda and Dunne, 1997a). However, Lancaster *et al.* (2001) suggested that LWD attenuates the movement of sediment in headwater streams such that coherent waves of sediment, as observed by Roberts and Church (1986), Miller and Benda (2000), or as modeled by Benda and Dunne (1997b), are not likely to occur where wood debris dominates the channel. However, LWD can act as a "valve" by temporarily storing and then releasing sediment from an advancing wave front. The Lancaster *et al.* (2001) model does not account for such a sediment wave. LWD jams are rarely tight, but release sediment as they partially float during a high flow event, when they often shift or break up. Thus, the wave does not disappear but is modified by punctuated and complex storage and releases by wood.

Models of Bed Material Transport

In headwater streams, predictions of sediment transport rate via hydraulically-based functional relations are often an order of magnitude greater than measured rates. These discrepancies have been explained by the dominance of step pool and boulder morphology, heavy bed surface armoring, and low sediment availability. Sawada *et al.* (1983) examined the impact of step pool morphology on the total bed load. They showed major shifts in bed load discharge relations as a result of variations in the volume of gravel stored in the pools. Discrepancies also are related to the assumptions that underlie the models: uniform sediment, general movement of sediment, and no consideration of the impact of sediment supply on sediment mobility. For modeling sediment transport in headwater streams it is important to distinguish between phases of transport and to recognize supply-limitation or transport limitation. More than two orders of magnitude variability in sediment transport have been attributed to in-channel scour (e.g., Jackson and Beschta, 1982) and to episodic supply of sediment from external sources (e.g., Hayward, 1980).

Recognition of the distinct character of steep mountain streams has prompted focused flume and field studies (e.g., Mizuyama, 1977; Smart and Jaeggi, 1983; Rickenmann, 1990; D'Agostino and Lenzi, 1999; Lenzi *et al.,* 1999). After experimental trials, Smart and Jaeggi (1983) extended the well known Meyer-Peter and Muller (1948) bed load formula to gradients of about 20 percent (11 degrees). Bathurst *et al.* (1987) modified Schoklitsch's (1962) formula for channels with up to 9 percent (5 degrees) gradient, but noted limited predictive success in rivers where sediment supply limitation is an important problem. Rickenmann (1990) conducted steep flume experiments using various clay concentrations in water. He developed a formula to calculate sediment transport for both clear water (no clay) and hyperconcentrated flows on gradients ranging between 5 and 20 percent by modifying the Bathurst *et al.* (1987) formula through the addition of a suspension density factor.

A large number of deterministic and stochastic mathematical models have been developed to describe sediment transport. Most formulae are based on tractive force or on the concept of stream power, both of which are highly correlated, in the mean, with streamflow. The complex nature of sediment transport leads to a situation in which almost all bed load equations contain, directly or indirectly, an empirical element. The performance of bed load formulae in steep mountain streams was tested by D'Agostino and Lenzi (1999). They reported good agreements between measured and computed bed load volumes, over time interval ranging from a few tens of minutes to the whole flood, using Bagnold's (1956) formula, the Smart and Jaeggi (1983) extension of the Meyer-Peter and Muller formula, and Rickenmann's formula (1990, 1992). Modification of the Bathurst et al. (1987) formula also provided reasonable estimates for instantaneous transport rates and limited sediment supply conditions.

The relevance of formulated transport relations in headwater streams remains limited. In the dominant, tractive force approach, flow depth is part of the stream force calculation. Due to the difficulty of measuring depth accurately in boulder bed streams, estimates of the mean flow depth using conventional methods are highly unreliable and are often subject to significant errors. Field studies often report water discharge, and so the transport function is converted to a discharge-based correlation (e.g. Schoklitsch, 1962; Bettess, 1984; Ferguson, 1994; Lenzi *et al.,* 1999; D'Agostino and Lenzi, 1999).

Since bed material transport occurs during short periods of time, seasonally and within single flow events, wholly empirical rating curves relating sediment transport rate to flow discharge have also been studied, but results are highly unstable and site specific (Hassan and Church, 2001). Where hysteresis is present, no single rating relation between sediment and water discharge can be applied to both rising and falling flow stages, or to all events (Klingeman and Emmett, 1982; Hassan and Church, 2001). For these reasons only a limited number of studies have explored the possibility to apply rating curves to the prediction of sediment transport rates (e.g., Adenlof and Wohl, 1994; Moog and Whiting, 1998; Emmett and Wolman, 2001).

For the development of a reliable model, a better understanding of the relations amongst flow, sediment transport, and sediment supply is needed. A sophisticated model of channel bed stability will be required to describe conditions in structured mountain channels, and it appears that a successful model for sediment transport in such channels will have to incorporate some information about sediment supply. These circumstances greatly complicate information requirements for modeling.

CHANNEL MORPHOLOGY

The channel morphology of headwater streams is influenced by nonfluvial inputs of sediment and wood from adjacent slopes. Boundary elements include bedrock, hillslope colluvium, and rooted vegetation. There is also a continuum of particle sizes in upland channels from those that move frequently to those that do not move at all. The channel may incorporate lag boulders of the same size as channel depth (Grant *et al.,* 1990; Church, 1992) or larger. Accordingly, their morphology reflects the irregular addition of non-alluvial elements and alluvium forced into storage by those elements. The objectives of this review include the following: to describe reach morphology in small, forested streams; to describe channel unit morphology in small alluvial streams; and to describe briefly the forced channel morphologies associated with LWD.

Reach Morphology

A reach is a length of channel under the influence of uniform governing conditions, hence exhibiting uniform morphology. Channel reaches are several (usually > 10) to many channel widths in length (Montgomery and Buffington, 1998). The reach may be characterized by hydrology, bed material, bed forms, channel planform, ecology, or a combination of all these features (Wohl, 2000). Headwater reaches are classified into bedrock, colluvial, and alluvial types, described briefly in the following paragraphs (for more detailed descriptions see Benda and Dunne, 1987; Grant *et al.,* 1990; Montgomery and Buffington, 1997; and Wohl, 2000).

Bedrock reaches lack alluvial deposits. They are characteristically steep and sediment supply limited (sediment transport capacity is greater than supply rate). Bedrock reaches are usually located in the uppermost part of steep drainage basins. Constrained by rock outcrops, they differ in form and development from alluvial reaches. Their characteristics are determined jointly by flow and sediment transport rate – which influence abrasion of the rock boundary – rock jointing and/or bedding, and the resistance of bedrock to abrasion and weathering processes, which influence the rate and style of erosion (see Tinkler and Wohl, 1998). Temporary storage of material supplied by episodic events can change bedrock reaches into colluvial reaches (Benda, 1990) whereas debris flows may scour the reach, exposing bedrock (Swanston and Swanson, 1976; Grant *et al.,* 1984).

Colluvial reaches are channels that contain material derived from adjacent hillslopes. A variety of processes supply sediment to the reach, including soil creep, surface erosion, debris slides, tree throw, and burrowing by animals (Roberts and Church, 1986; Benda and Dunne, 1987; Montgomery and Dietrich, 1988; Montgomery and Buffington, 1998). Such reaches normally have insufficient stream power available to transport the boulders and wood pieces introduced into the channel (Montgomery and Buffington, 1998) which, along with bedrock steps, constitute large roughness elements.

Alluvial reaches are channels that contain stream deposited sediments. They are transport limited channels characterized by a wide range of bed morphologies reflecting the interactions amongst flow regime, sediment supply rate and characteristics, sediment transport regime, and geomorphic and geologic setting (e.g., gradient, confinement, lag deposits). Channel morphologies in alluvial reaches in small, forested streams are described in the section following.

Montgomery *et al.* (1996b) examined the distribution of reach types in forested streams. They described the threshold between bedrock and alluvial channels using a model that relates the local sediment transport regime to the sediment supply. The threshold for the excess of either sediment or sediment transporting capacity is expressed in terms of slope and drainage area (Figure 3).

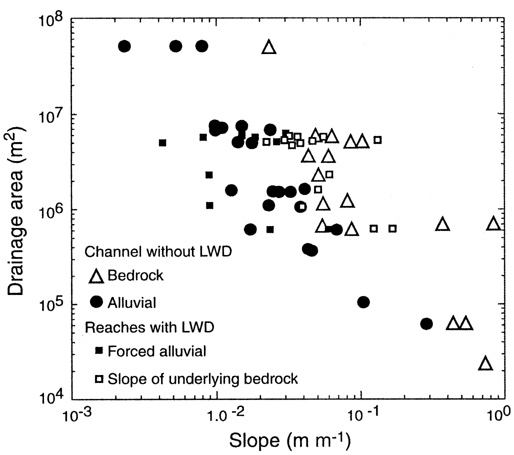

Figure 3. Drainage Basin Area Versus Reach Average Slope for Basins in the Olympic Mountains, Washington (after Montgomery *et al.,* 1996b, Figure 1, p. 587).

Montgomery *et al.* (1996b) found that inputs of LWD to bedrock reaches could force the establishment of alluvial reaches. In a more detailed, field-based study, Massong and Montgomery (2000) examined the influences of lithology, local variation in sediment supply, and LWD on the distribution of bedrock and alluvial reaches in mountain streams. Their field evidence confirms the assumption that LWD can change a bedrock reach into an alluvial reach. Average gradient is reduced significantly where the change occurs. Furthermore, they reported that the bedrock alluvial threshold varies with lithology, sediment supply, and local flow obstructions. They concluded that, in their study area, the LWD distribution exerts a strong influence on the distribution of bedrock and alluvial reaches.

Channel Unit Morphology

A channel unit is a morphologically distinct portion of channel, usually one to a few channel widths in length. Mountain headwaters exhibit very variable units (Grant *et al.,* 1990; Hawkins *et al.,* 1993), over which there is some confusion of terminology. Here, the most commonly used terms are adopted, following the summary given in Table 3. For practical reasons, also, "forced" and "free" morphologies are distinguished. This distinction creates some problems because step-pool is included in the free morphologies (as is usual in the literature) yet it is in fact a forced one.

Boulder Cascade. Boulder cascades are steep channels characterized by longitudinally and laterally disorganized cobbles and boulders with small, non-channel spanning "pocket" pools among them (Sullivan, 1986; Montgomery and Buffington, 1993, 1997, 1998). During low to moderate flow events in cascade reaches, fine gravels move whereas boulders are rarely mobile (Grant *et al.,* 1990). Grant *et al.* (1990) described the flow in cascade reaches as water tumbling over boulders and turbulence around them which dissipates flow energy (see also, Sullivan, 1986; Montgomery and Buffington, 1997). Relative roughness is near or greater than 1.0. Such reaches are found on gradients greater than 4 percent, mainly considerably greater and, in the smallest channels, may be as steep as 45 percent (Halwas and Church, 2002). They probably form by limited movement and stabilization of lag colluvial boulders and quite probably should be regarded as a colluvial, rather than an alluvial, morphology.

Step-Pool. Channel steps, formed by boulders or logs, create significant channel morphologies in small streams (e.g., Hayward, 1980; Likens and Bilby, 1982; Chin, 1989; Grant *et al.,* 1990). At low flows, they appear as a series of steps with water moving slowly through pools and flowing over steps into the next pool, forming a waterfall (Hayward, 1980). At high flow, relative roughness is near 1.0. Step pool sequences are characteristic features of headwater streams with average reach gradients greater than 3 percent (Hayward, 1980; Whittaker, 1987; Chin, 1989; Abrahams *et al.,* 1995; Gomi *et al.,* 2003) and occur at gradients up to 30 percent (Montgomery and Buffington, 1997; Halwas and Church, 2002). Judd and Peterson (1969) reported that the more steep the channel gradient becomes, the more prominent and

TABLE 3. Summary of Channel Unit Morphology and Gradient Ranges of Steep, Clastic Channels.

Reference	Pool	Glide	Riffle	Rapid	Cascade	Comments
Bisson *et al.,* 1981			S < 0.04	S > 0.04	Steepest rock, boulder, or LWD jams	Many channel subunits identified
Sullivan, 1986	S < 0.01 dammed, 0.002 scour, 0.006 plunge, 0.009	0.01<S<0.02	0.01<S<0.04 <S> = 0.022	S>0.04 <S> = 0.07	0.04<S<0.16 <S> = 0.068 (a) step pool (b) slip face	Channel units are 4-8w in length
Grant *et al.,* 1990	S ~ 0.005 tranquil flow	–	<S> = 0.011 not ribbed	<S> = 0.029 ribbed	<S> = 0.055 boulder; bedrock	Channel subunits 0.4-0.8w; channel units 1-10w; channel reach 100-1,000w; steps have <S> = 0.17
Wood-Smith and Buffington, 1996	closed topography depression: (a) obstructed (b) not obstructed	S_b<0.02	0.02<S_b<0.04	–	S_b>0.04	Modified from Bisson *et al.* (1981), and Sullivan (1986); overall stream gradients <0.025
Montgomery and Buffington, 1997	<S> = 0.012 for pool/riffle unit S<0.031; <0.036 forced by LWD	"plane bed" <S> = 0.023 0.0015<S <0.04	–	"step pool" <S> = 0.044 0.02<S <0.076	<S> =0.11 0.020<S<0.20	Gradients are means over several channel widths
Halwas and Church, 2002	Closed topography depression (a) dammed (b) plunge pool	<S_b> = 0.06	<S_b> = 0.09	step pools <S_b> = 0.20	<S_b> ~ 0.45 (boulders) <S_b> ~ 0.49 (rock)	Small channels, S_b<0.25, generally
Summary	Closed depression	S<0.02	S<0.04	S<0.10; D/d<1.0	S>0.04; D/d>1.0	

Notes: S = water surface slope; S_b = bed slope; <S> = mean water surface slope; <S_b> = mean bed slope; D/d = relative roughness (D = particle size; d = water depth). Most results follow Bisson *et al.* (1981), and Sullivan (1986), with amendments by Grant *et al.* (1990). The results of Montgomery and Buffington (1997), and of Halwas and Church (2002) are not comparable with the rest. Montgomery and Bufffington (1997) measured mean gradients over some distance; Halwas and Church (2002) observed much smaller streams than all others (from Church, 2002, Table 1:547; and Halwas and Church, 2002, Table 6:255).

regularly spaced the steps. Abrahams *et al.* (1995) suggested that step pools maximize resistance, therefore stabilizing the bed surface. Both field and flume studies support these findings.

Grant *et al.* (1990) listed conditions for the development of step pools: low sediment supply, large boulders, immobile except during the largest events (hence the claim that these are forced morphologies), and channels with a low width-to-depth ratio. There remains controversy over the mechanism of step formation (compare Grant, 1994; Abrahams *et al.,* 1995; Chin, 1999; Zimmerman and Church, 2001). Step height is largely controlled by the size of the forming boulders, whilst step length and slope are negatively related (Whittaker, 1987; Chin, 1989; Grant *et al.,* 1990). This implies that step size is close to constant along a reach, any increase in channel slope being modulated by reduced spacing between the steps (Knighton, 1998). It has been suggested that step pools are insensitive to change in flow regime even during extreme conditions (Ryan, 1994) and to both sediment yield and flow regime changes caused by timber harvesting (e.g., Madsen, 1995; Montgomery and Buffington, 1997).

Rapid (plane bed). Ikeda (1975) and Montgomery and Buffington (1997) described relatively featureless gravel channel units with moderate gradients in which pools are typically absent as "plane beds." To avoid confusion with the plane bed regime well established in sand bed hydraulics, Zimmerman and Church (2001) suggested the term "rapid" for this morphology. The typical range of gradients is 2 to 10 percent and relative roughness is of order 0.5 to 1.0. The well armored surface (Buffington, 1995; cited in Montgomery and Buffington, 1998) is associated with features such as clusters, stone lines, and stone nets (Church *et al.,* 1998) that indicate relative stability and a supply limited sediment transport regime (cf., Dietrich *et al.,* 1989). Partial destruction of the bed surface, typically at near-bankfull flow, may increase the transport rate from Phase I to Phase II (Church *et al.,* 1998; Hassan and Church, 2001). According to Montgomery and Buffington (1997) rapid reaches represent a transition between supply limited and transport limited reaches.

Pool and Riffle. Pool and riffle morphology is associated with floodplains and they are important aquatic habitat (e.g., Leopold *et al.,* 1964; Sullivan, 1986). In gravel bed rivers the channel bed undulates in alternating shallow zones called riffles and deep zones called pools (e.g., Leopold *et al.,* 1964; Keller, 1971; Sullivan, 1986; Grant *et al.,* 1990; Montgomery and Buffington, 1997). Pool riffle morphology forms in reaches with gradient less than 2 percent and is well expressed at gradients of order 1 percent and less. The riffles and associated barforms consist of vertically piled accumulations of many clasts, so relative roughness is much less than 1.0. Riffles mediate energy expenditure in a manner that promotes channel stability. These elements appear to develop by selective scour and deposition along the channel so that relatively large material collects (or remains exposed) on the riffles. Alternatively, nonfluvial features, such as exposed bedrock, rockfall or landslide debris may form such a feature.

In free formed pool riffle reaches, the pool/pool spacing averages five to seven channel widths (Leopold *et al.,* 1964). Shorter spacing, between 1 and 5 channel widths, has been reported for forest streams (e.g., Keller *et al.,* 1981; Grant *et al.,* 1990; Hogan *et al.,* 1998). It has been suggested that the wide range of values obtained for forested streams is related to non-alluvial pool forming features such as LWD jams (Myers and Swanson, 1997; Hogan *et al.,* 1998). Montgomery *et al.* (1995) reported that pool spacing indeed depends on LWD loading as well as channel type, slope, and width.

Forced Morphology. In forested streams, LWD and bedrock outcrops influence channel morphology, flow and sediment transport (e.g., Lisle, 1986; Hassan and Woodsmith, 2004). These elements cause "forced" morphologies (Montgomery and Buffington, 1993, 1997). Log steps are one of the most common features in small, forested streams. They form when individual pieces of wood come to rest across a channel (e.g., Hogan, 1986). Like boulder or rock steps, log steps create a stepped longitudinal profile, alter flow, dissipate energy, and store sediment (e.g., Keller and Swanson, 1979). Transversely oriented logs are associated with plunge pools and hydraulic jumps which are very effective in dissipating energy and storing sediment (Keller and Swanson, 1979; Montgomery and Buffington, 1997, 1998). Obliquely oriented logs are associated with scour pools and store sediment on both sides by upstream buttressing and downstream low energy zones (Smith *et al.,* 1993b; Montgomery and Buffington, 1998). In forested streams, LWD alters the flow pattern and sediment passage, which may lead to the development of forced riffle pool morphology on a gradient reduced by sediment accumulation (Montgomery and Buffington, 1997, 1998). Forced pool riffles associated with LWD may replace rapid or bedrock channels (Montgomery *et al.,* 1995). Furthermore, Montgomery and Buffington (1998) speculated that LWD might force the development of step-pool features in cascade or bedrock channels.

Stream Classification

Streams are complex systems that defy simply classification. Stream classification depends upon the purpose and the type of data available and remains essentially subjective. Several methods of stream classification have been suggested, based on hydrological, geomorphological, and ecological characteristics of the fluvial system. Stream classifications for hydrological research have been based, among other criteria, on flow regime classifications (Jones and Peters, 1977), average monthly flow, average daily flow (Poff and Ward, 1989), and on flow indices (Hughes and James, 1989). From a practical point of view these classifications are probably most appropriate at a regional scale.

Most stream classifications used in ecological research are based on the premises that channels consist of distinct physical elements (units) such as riffles, pools, and steps, and that these features each have intrinsic and distinct ecological value (Bisson *et al.,* 1981). Therefore, underlying most habitat classifications is a geomorphological framework, but rarely is that connection formally made. The ecological value of a habitat type may be defined, for example, in terms of fish density, insect production, or primary production. All animals including fish are habitat specialists and habitat classifications attempt to recognize which channel features (i.e., habitat types) are used by which species throughout its various life stages. The "litmus test" for a habitat classification is whether or not ecological patterns (e.g., species distribution and production) along a channel match the boundaries of the physically defined habitat units (Hawkins *et al.,* 1993).

Few geomorphologically-based stream classification systems have been proposed that discriminate amongst smaller streams. Rosgen's (1994) channel classification scheme produced 41 channel types based on channel boundary conditions, entrenchment ratio (which expresses the degree of lateral confinement), sinuosity (the degree of meandering), width/depth ratio (channel shape), and channel slope. Small, forested streams are classified as Rosgen Types A and B. In Type A, the entrenchment ratio is less than 1.4, width/depth ratio is less than 12, sinuosity is less than 1.2, and the gradient is greater than 0.04; in Type B, entrenchment ratio is 1.4 to 2.2, width/depth ratio greater than 12, sinuosity greater than 1.2, and gradient 0.02 to 0.1. Superficially, the gradients assigned to these types appear to distinguish channels apt to have structured beds (rapids, step pool, cascades) and limited sediment supply from ones without (riffle pool). Insofar as the latter channels are usually larger, being found farther down the drainage system, the discrimination of width/depth ratio is superficially plausible, as well. But there seems to be no essential reason for consistency in the remaining characteristics.

Montgomery and Buffington (1998) point out that the Rosgen classification is not process-based and lacks any rational explanation of response potential for each channel type. However, a superficially similar classification was proposed by the Scientific Panel for Sustainable Forest Practices in Clayoquot Sound (1995) for purposes of headwater channel management. Fundamental distinctions were made between alluvial and nonalluvial channels (reaches), between ones with gradient less than 8 percent and greater, between entrenched and not entrenched, and width classes less than 3 m ("small channels" herein), less than 30 m ("intermediate channels" herein), and larger ones. For very steep channels (S > 20 percent) discrimination was also made between seasonal and ephemeral flow regimes. The gradient distinction was based on probability for fish presence. Such a classification was adopted by the Panel for purely pragmatic reasons: it was considered possible to identify and classify channels on these criteria using map evidence and walk through inspections only, the usual sources of information in land management exercises.

The British Columbia channel classification system (British Columbia Ministry of Forests, 1996a,b; Hogan and Bird, 1998), again developed explicitly for aquatic resource management purposes, is based on field measurements and makes use of earlier typologies by both Grant *et al.* (1990) and Church (1992). It combines channel relative size and boundary conditions with the bed material and LWD conditions to produce seven channel types (Table 4). Each of the seven channel types is then assigned a disturbance state based on field indicators of disturbance, which include sedimentological, bank, morphological, and LWD features.

Whiting and Bradley (1993) have developed a process-based classification of headwater streams based on the domains in which various processes act (Figure 4). The primary variables that are likely to control the stream ecosystem and sediment mobilization in headwater streams include: (1) hillslope gradient, which determines slope stability and mass movement magnitude, frequency, and type; (2) channel gradient which determines stream power (shear stress); (3) valley bottom width (defined as the distance between opposing valley sideslopes at the base of these slopes), which influences flood hydrology and determines whether debris flows coming off adjacent slopes will enter the stream; and (4) sediment caliber, which determines movement modes and the amount of sediment transport. They included two response elements: (1) channel width, which indicates the degree to which the hillslope contributes material directly to the channel (e.g., a wide valley bottom, but

TABLE 4. British Columbia Channel Types and Associated Characteristics (after British Columbia Ministry of Forests, 1996a,b).

Code	Morphology	Subcode	Bed Material	LWD
RP	Riffle pool	RP_g-w	Gravel	Present, major function
RP	Riffle pool	RP_c-w	Cobble	Present, major function
CP	Cascade pool	CP_c-w	Cobble	Present, minor function
CP	Cascade pool	CP_b	Boulder	Absent
SP	Step pool	SP_b-w	Boulder	Present, minor function
SP	Step pool	SP_b	Boulder	Absent
SP	Step pool	SP_r	Boulder block	Absent

Notes: Wood functioning implies that the arrangement of the channel is controlled largely by wood and sediment transport occurs in conjunction with wood transport. Minor function is when wood is present and may influence small portions of the channel but sediment transport is largely controlled by flow hydraulics and channel morphology.

one entirely taken up by the channel, will not have a valley flat on which to trap sideslope debris flows); and (2) channel depth, which, with channel gradient, determines the shear stress. The resulting classification is presented in Figure 4.

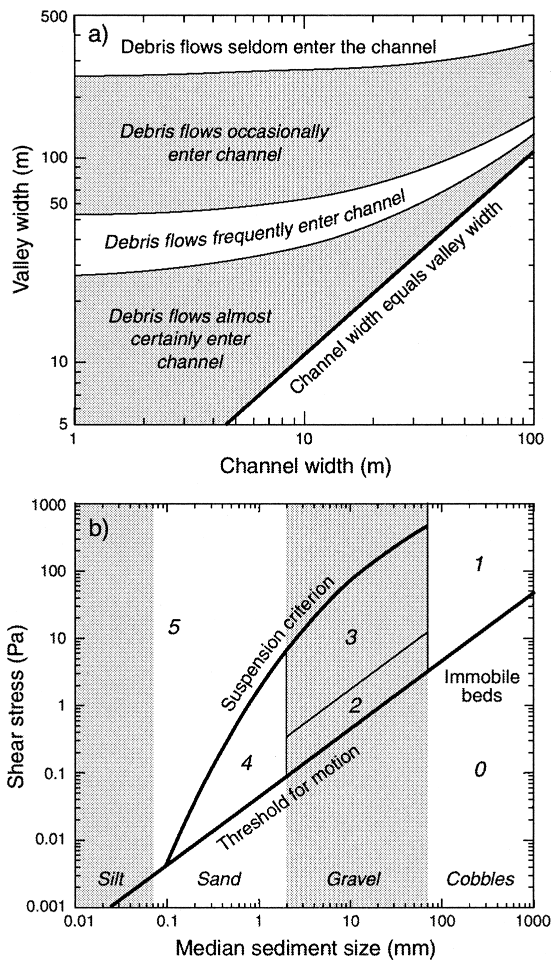

Figure 4. Figure 4. Process-Based Stream Classification System (a) Characterizing the Degree of Hillslope Interaction With the Channel, and (b) Characterizing the Transport of Material in the Channel (modified from Whiting and Bradley, 1993, Figure 1:607).

There are six domain classes in Figure 4b. Class 0 represents channels in which sediment remains immobile in all but extreme events. In Class 1, sediment is above the criterion for motion in formative events and grain size is coarser than 64 mm. In Class 2, the mobile fine gravels to cobbles are armoured and shear stresses are never greater than three times the critical value needed for initial movement. In Class 3, the mobile gravel to cobble bed is unarmoured because shear stresses are more than three times the threshold for motion. In Class 4, the unarmoured, and primarily sand, bed carries most of its load in saltation. In Class 5, sediment finer than sand moves primarily in suspension.

The foregoing classifications, except the British Columbia channel classification system, are not comprehensive because they do not consider the impact of wood on channel morphology in forested streams (Montgomery and Buffington, 1998). Montgomery and Buffington (1993, 1997) proposed a framework for classifying mountain streams based on the fundamental relation that exists between bed surface roughness, sediment supply, and sediment transport capacity, which links processes to form in stream channels. Because channel morphology is likely to be affected by external controls such as coupling and LWD, they combined these external conditions with the sediment transport regime to classify channel units into reach scale aggregations. Their classification scheme was tested using data collected from Oregon and Washington streams. The results of this test suggest that each channel type occurs within a limited range of slope classes, confirming the findings of Grant *et al.* (1990). Myers and Swanson (1997) have subsequently detected a significant link between pool spacing and Montgomery and Buffington's (1993) stream types.

SLOPE CHANNEL INTERACTIONS

The Disturbance Cascade

A cascade is a system though which mass and energy passes, a formal representation of a process involving mass transfer. This usage is entirely distinct from that which denominates a channel type, described earlier. A range of geomorphic processes operates in mountain watersheds that can be linked sequentially to define a disturbance cascade which moves from slopes into the channel network.

Although the importance of coupling between stream channels and the adjacent hillslopes has been long acknowledged, relatively little work has attempted to characterize its role in the context of the sediment cascade through the fluvial system. In coupled systems, both hillslope and fluvial processes control channel morphology; the former are likely to be dominant. Nakamura *et al.* (2000) considered two classes of hillslope processes: small, rapid movements of debris from hillslopes to channels and large, slow movements of earth material. Small, (10 to 1,000 m^3) episodic debris slides are initiated on slopes and move into headwater streams. Slow but large (1-100 ha) movements of material include earthflows and rock sags that slowly force material into the channel by the mechanism of bank erosion. Low order streams in steep mountainous regions are typically small, steep, and contain coarse material. The hydrological regime is flashy and channel stability is controlled by forced bed forms (e.g., step pool). Field work shows that first order streams might become clogged with sediment delivered from hillslopes and that stream flows generated by small drainage basins are too small to remove all of the supplied material, especially the coarser material (e.g., Benda, 1990).

Debris slides initiated on steep hillslopes enter channels and may propagate into debris flows that eventually come to rest somewhere downstream near tributary confluences or in low gradient reaches (Benda, 1990). The region of debris flow deposition is still well upstream in the channel network (often at junctions of first-order and second-order channels, at the base of valley side slopes). In some situations, high pore pressure at the head of steep first-order channels directly generates debris flows, thereby extending the channel network headward (cf., Montgomery and Dietrich, 1988).

In third order and larger streams, side slope colluvium and episodic side slope debris slides continue to supply coarse material to the channel. Basin history governs the volume of sediment and wood stored on hillslopes and in channels, hence controlling their redistribution by flow events. In contrast to upstream sites, the flows are sufficient to move most of the sediment downstream. Channel morphology is dictated by the location and volume of sediment and wood supplied to streams. Long term effects of sediment and wood transport are the creation of LWD jams, log steps, accumulation of boulders, and the construction of alluvial fans (Benda, 1990; Benda *et al.,* 1998). Channels are often bounded by narrow flats that may represent flood benches, debris flow berms, and/or side slope colluvial fans (e.g., Benda, 1990; Church and Ryder, 2001).

Processes in channels control how sediment and wood are transported onward through linked stream reaches. Benda and Dunne (1997b) developed a sediment routing model which is based on the stochastic supply of sediment to the channel network in a drainage basin. Episodic sediment inputs condition pulse like movement of dispersing "waves" through the channel system. Consequently, it appears that, for most of the time, headwater streams are sediment-starved (Lancaster *et al.,* 2001). It is apparent from both experimental and field studies (Lisle *et al.,* 1997; Sutherland *et al.,* 2002, and references therein) that gravelly inputs to streams are dominantly dispersive (Lisle *et al.,* 2001), with little or no translation. Material caliber and the selectivity of fluvial transport will have a substantial influence on the results. Hence, the condition of channels anywhere in the network will, in the end, depend upon the relative time scales of sediment supply and in-channel dispersion. In the very long term, weathering of lag materials also may become important.

Impact of Timber Harvesting and Roads on Sediment Mobilization

Forest harvesting practices consisting of road building, logging and slash burning can significantly alter the production and transport of clastic sediment. The impacts of forest harvesting have been studied for several decades, allowing some general inferences to be made. In most cases, study basins have been drained by relatively steep, low order streams with rock or gravel bed channels.

Harvesting can indirectly influence sediment transfer by altering the hydrology of harvested basins. Road building and clear cutting can alter both the timing and the magnitude of storm runoff events, which can cause changes in fluvial sediment transport. However, land use may have more direct effects by making much more sediment available for transfer as the result of soil exposure and disturbance, altered slope stability, damage to streambanks, and the emplacement of forest debris in gullies and stream channels. The consequences of harvesting related changes of streamflow are almost always confounded with changes in sediment mobilization due to surface disturbance and altered stability of stored sediment. This review emphasizes sources and mobilization of sediments.

Most studies in the Pacific Northwest have emphasized acceleration of mass wasting processes following road construction and clearcutting (e.g., Brown and Krygier, 1971; O'Loughlin, 1972; Swanson *et al.,* 1982c; Rood, 1984; Sauder *et al.,* 1987; Rood, 1990; Grant and Wolff, 1991; Megahan and Ketcheson, 1996). Logging activities affect hillslope stability by reducing or removing root reinforcement, increasing site disturbance, and modifying water interception and conveyance (Sidle *et al.,* 1985; Bovis *et al.,* 1998). Forest practices may increase the incidence of episodic mass wasting events up to ten times and sediment yield by two times or more (Table 1). Hence, post-harvest mass wasting alters the balance between sediment supply and transport in stream channels, thereby changing the channel morphology.

The deposition of sediment in channels alters channel gradient (Hogan *et al.,* 1998; Montgomery and Buffington, 1998). A large accumulation of sediment may force a lateral shift in unconfined channels, diverting the flow and causing bank erosion. These sediment inputs change through the drainage network, leading to changes in channel stability and stream ecology. The impact of episodic mass wasting events depends on whether they occur in close succession (Montgomery and Buffington, 1998) or only occasionally (Gomi, 2002). Bunched events are likely to clog confined channels with large amounts of sediment and wood over a relatively short period of time and are likely to bury the pre-existing local morphology (e.g., Benda and Dunne, 1997a; Montgomery and Buffington, 1998). Occasional events are likely to sustain chronic, though less extreme, impacts on the channel over longer periods of time (Gomi, 2002).

Road related mass wasting is a major source of sediment (Reid *et al.,* 1981; Reid and Dunne, 1984). Several studies (Schwab, 1983; Reid and Dunne, 1984; Rood, 1984; Rollerson, 1992) have shown that logging roads alone can account for up to 90 percent of the increases in slope failures and sediment delivery to stream channels. Slaymaker (2000) asserted that the failure to avoid unstable terrain during road construction and lack of maintenance of road drainage structures are the main factors causing road related failures. Unsurfaced roads also increase the rates of fine sediment production and the amount which is delivered to streams (e.g., Megahan and Kidd, 1972; Janda *et al.,* 1975; Reid and Dunne, 1984), with consequent impacts on downstream water quality and aquatic habitat. Reported road surface erosion rates encompass a wide range from a few millimeters per acre per year to tens of millimeters per acre per year (e.g., Dyrness, 1970; Megahan *et al.,* 1983; Riley, 1988). Although roads increase sediment transport rate by both mass wasting and fluvial processes, they also can function as storage sites by trapping sediment in ditches (e.g., Wemple *et al.,* 2001) and mass movement transported soil and debris in the road prism.

Wemple *et al.* (2001) examined the impact of forest roads on the initiation, movement, and interception of sediment during an extreme storm event in the Lookout Creek and Blue River basins, Oregon. Despite the dual function of roads as both sediment source and depositional sites for mass wasting, the net effect of roads was an increase in the basin sediment production. Fransen *et al.* (2001), in a New Zealand study, reported an increase of three orders of magnitude in erosion rates, but also a decline of mass wasting rates with road age (Fransen *et al.,* 2001). Luce and Black (2001) monitored sediment loss from road segments that covered a range of soil textures, gradients, plot lengths, and cut slope heights. In general, however, the particular location of study sites, the recent history of the roads, and the small scale of study plots make it difficult to extrapolate results to watershed scale (Dunne, 2001).

The timing of logging activity relative to large storms is important. Using a paired watershed approach, Grant and Wolff (1991) documented 30 years of sediment mobility (suspended and bed load) from three small basins with different road building and forest cutting treatments. A single event in 1964 transported about 85 percent of the total 30-year load. Consequently, they believe that even long term studies using paired watersheds have limited generalizing value, hence applicability, in places where episodic supply and transport dominate the landscape.

There are two ways to mitigate sediment delivery to streams: reduce the volume of erosion through onsite control practices and reduce sediment delivery by increasing sediment retention on the hillside (Megahan and Ketcheson, 1996). Madej (2001) examined the impact of different types of treatment to abandoned logging roads in California. She found that sediment production from treated roads contributed about 25 percent of the sediment produced from untreated roads. Also, hillslope position was an important variable in explaining the post-treatment erosion of road reaches; erosion problems were most common on steep, lower hillsides. She concluded that road treatment significantly reduced the long term sediment risk from abandoned roads.

The influence of roads on slope stability and sediment delivery to channels depends on road location, construction practices, physiographic conditions of the basins, and storm characteristics (Wemple *et al.,* 2001). Within the last 20 years, there have been major changes in accepted road management practices which have resulted in better road designs and decreased sediment transport to channels (Slaymaker, 2000). There remains a significant need to extend knowledge of road effects from individual segments to road networks.

CLOSING REMARKS

Channel processes and morphology in forested, small streams are controlled by several governing conditions including water discharge, availability, and texture of sediment supplied to or stored in channels, wood supply to channels, channel gradient, and the conditions of bank vegetation. Sediment supplied from slopes and stored within the channel is the main control on channel morphology. Sediment transport in these streams reflects the balance between supply and transport capacity. Episodic sediment supply causes the channel to alternate over time between supply limited and transport limited situations. The impact of episodic sediment supply on channel morphology remains poorly understood and needs to be addressed in future research.

Channel morphology and bed surface structures control channel stability in headwater streams. Channels are considered to be stable with little sediment movement between major sediment supply events from the adjacent hillslopes. Based on field measurements, three phases of sediment transport have been identified: overpassing fine sediment (Phase I), partial mobility of local sediment (Phase II), and mobilization of most of the sizes found in the bed (Phase III). In headwater streams, Phases I and II dominate the sediment transport regime, while Phase III occurs only during relatively extreme flow events. In steep channels, Phase III transport leads to debris flows. Due to the major impact of bed surface structures on sediment mobility, the usefulness of current sediment transport models developed for lowland streams is limited. A successful model should take into account the bed surface structure. Such a model still needs to be developed.

Forest management in small, forested basins is likely to change water, sediment, and wood inputs to channels and significantly affect channel morphology, channel stability, and aquatic habitat. However, due to the conditionally stable nature of the step pool and log step morphologies, changes in the flow alone are not likely to have a real impact on the stability of such structures (Grant *et al.,* 1990). Poor harvesting practices on relatively unstable slopes and poor road design can lead to changes in the amount and texture of sediment supplied to channels, and the amount and characteristics (e.g., piece size) of wood inputs. High quality roads and better maintenance are likely to reduce the amount of material supplied to channels from hillslopes, reduce the amount of sediment mobilized along low order streams, and reduce the sediment delivery rate to high order streams (Slaymaker, 2000).

In a review paper, Dunne (2001) provided a critical assessment of the limitation of field and modeling programs in the context of land management. According to Dunne (2001), one of the main problems of measuring and predicting the influence of forest management practices is that monitoring programs in most forested area are typically too short to sample the variability of natural and disturbed hydrological regimes, increasing the likelihood of missing significant sediment mobilization events. This implies that sample sizes are often too small to address questions such as "Does logging increase the risk of mass wasting and flooding?" Furthermore, the number of monitoring sites remains small, which leads to another constraint on the ability to assess the impact of forest harvesting on channels and slopes (Dunne, 2001). To solve these problems, well designed long term field programs are needed that pay appropriate attention to spatial variation of hydrological and geomorphological processes in the landscape, as well as to accumulating adequate temporal records. Many of the observations will have to be made as part of operational management of the land. Accordingly, the authors' advice to land managers is "tuum est," or "it is yours."

ACKNOWLEDGMENTS

The authors thank Steve Bird, John Buffington, Takashi Gomi, Dan Hogan, Dave Montgomery, Sandra Ryan, and Rick Woodsmith for data, suggestions, and/or review comments received during the writing of this paper. The authors also acknowledge the constructive comments of two anonymous reviewers.

LITERATURE CITED

Abrahams, A.D., G.Li, and J.F. Atkinson, 1995. Step-Pool Streams: Adjustment to Maximum Flow Resistance. Water Resources Research 31:2593-2602.

Adenlof, K.A. and E.E. Wohl, 1994. Controls on Bedload Movement in a Subalpine Stream of the Colorado Rocky Mountains, USA. Arctic and Alpine Research 26:77-85.

Andrews, E.D., 1979. Scour and Fill in a Stream Channel East Fork River, Western Wyoming. U.S. Geological Survey Professional Paper 1117, Washington, D.C., 49 pp.

Andrews, E.D., 1983. Entrainment of Gravel From Naturally Sorted River Bed Material. Geological Society of America Bulletin 94:1225-1231.

Andrews, E.D., 1984. Bed Material Entrainment and Hydraulic Geometry of Gravel Bed Rivers in Colorado. Geological Society of America Bulletin 95:371-378.

Ashworth, P.J. and R.I. Ferguson, 1989. Size-Selective Entrainment of Bedload in Gravel Bed Streams. Water Resources Research 25:627-634.

Bagnold, R.A., 1956. The Flow of Cohesionless Grains in Fluids. Philosophical Transactions of the Royal Society of London, Series A, 249:235-297.

Bathurst, J.C., W.T. Graf, and H.H. Cao, 1987. Bed Load Discharge Equations for Steep Mountain Rivers. *In:* Sediment Transport in Gravel-Bed River, C.R. Thorne, J.C. Bathurst, and R.D. Hey (Editors). Wiley and Sons, Chichester, United Kingdom, pp. 453-491.

Benda, L., 1990. The Influence of Debris Flows on Channels and Valley Floors in the Oregon Coast Range, USA. Earth Surface Processes and Landforms 15:457-466.

Benda, L. and T. Dunne, 1987. Sediment Routing by Debris Flow. *In:* Erosion and Sedimentation in the Pacific Rim. International Association of Hydrological Science Publication 165:213-223.

Benda, L. and T. Dunne, 1997a. Stochastic Forcing of Sediment Supply to Channel Networks From Land Sliding and Debris Flow. Water Resources Research 33:2849-2863.

Benda, L. and T. Dunne, 1997b. Stochastic Forcing of Sediment Routing and Storage in Channel Networks. Water Resources Research 33:2865-2880.

Benda, L.E., D.J. Miller, T. Dunne, G.H. Reeves, and J.K. Agee, 1998. Dynamic Landscape Systems. *In:* River Ecology and Management: Lesson From the Pacific Coastal Ecoregion, R.J. Naiman, and R.E. Bilby, (Editors). Springer-Verlag, New York, New York, pp. 261-288.

Bettess, R., 1984. Initiation of Sediment Transport in Gravel Streams. Proceedings of the Institution of Civil Engineers, 77, Part 2, Tech. Note 407, pp. 79-88.

Bilby, R.E., 1981. Role of Organic Debris Dams in Regulating the Export of Dissolved and Particulate Matter From Forested Watershed. Ecology 62:1234-1243.

Bilby, R.E. and P.A. Bisson, 1998. Function and Distribution of Large Woody Debris. *In:* River Ecology and Management: Lesson from the Pacific Coastal Ecoregion, R.J. Naiman and R.E. Bilby, (Editors). Springer-Verlag, New York, New York, pp. 324-346.

Bilby, R.E. and J.W. Ward, 1989. Changes in Characteristics and Function of Woody Debris With Increasing Size of Streams in Western Washington. Transactions of the American Fisheries Society 118:368-378.

Bisson, P.A., J.L. Neilsen, R.A. Palmason, and L.E. Grove, 1981. A System of Naming Habitat Types in Small Streams With Examples of Habitat Utilization by Salmonids During Low Stream Flow. *In:* Acquisition and Utilisation of Aquatic Habitat Inventory Information, N.B. Armantrout (Editor). American Fisheries Society Western Division, The Hague Publishing, Billings, Montana, pp. 62-73.

Blizard, C.R. and E.E. Wohl, 1998. Relationship Between Hydraulic Variables and Bedload Transport in a Subalpine Channel, Colorado Rocky Mountains, USA. Geomorphology 22:359-371.

Bovis, M.J. and B.R. Dagg, 1988. A Model for Debris Accumulation and Mobilization in Steep Mountain Streams. Hydrological Sciences Journal 33:589-604.

Bovis, M.J., T.H. Millard, and M.E. Oden, 1998. Gully Processes in Coastal British Columbia: The Role of Woody Debris. *In:* Proceeding of Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coast Research to Management Solutions, D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (Editors.). British Columbia Ministry of Forests Research Program, Victoria, B.C., Canada, pp. 49-75.

Brardinoni, F., O. Slaymaker, and M.A. Hassan, 2003. Landslide Inventory in a Rugged Forested Watershed: A Comparison Between Air-Photo and Field Survey Data. Geomorphology 54:179-196

British Columbia Ministry of Forests, 1996a. Channel Assessment Procedure Guidebook. Ministry of Forests and British Columbia Environment, Victoria, British Columbia, 37 pp.

British Columbia Ministry of Forests, 1996b. Channel Assessment Procedure: Field Guidebook. Ministry of Forests and British Columbia Environment, Victoria, British Columbia, 95 pp.

Brown, G.W. and J.T. Krygier, 1971. Clear-Cut Logging and Sediment Production in the Oregon Coast Range. Water Resources Research 7:1189-1198.

Buffington, J.M. and D.R. Montgomery, 1997. A Systematic Analysis of Eight Decades of Incipient Motion Studies, With Special Reference to Gravel-Bedded Rivers. Water Resources Research 33:1993-2029.

Buffington, J.M. and D.R. Montgomery, 1999. Effects of Supply on Surface Textures of Gravel-Bed Rivers. Water Resources Research 35:3523-3530.

Bunte, K., 1996. Analyses of the Temporal Variation of Coarse Bedload Transport and Its Grain Size Distribution. USDA, Forest Service, Rocky Mountain Forest and Range Experimental Station, Fort Collins, Colorado, General Technical Report RM-GTR-288, 123 pp.

Chin, A., 1989. Step Pools in Stream Channels. Progress in Physical Geography 13:391-407.

Chin, A., 1999. On the Stability of Step-Pool Mountain Streams. Geophysical Research Letters 26:231-234.

Church, M., 1978. Palaeohydraulic Reconstructions From a Holocene Valley Fill. *In:* Fluvial Sedimentology, A.D. Miall (Editor). Canadian Society of Petroleum Geologists, Mem. 5, Calgary, Canada, pp. 743-772.

Church, M., 1992. Channel Morphology and Topology. *In:* The Rivers Handbook, C. Calow and G. Petts (Editors). Blackwell, Oxford, United Kingdom, 2:126-143.

Church, M., 2002. Geomorphic Thresholds in Riverine Landscapes. Freshwater Biology 47:541-557.

Church, M. and M.A. Hassan, 2002. Mobility of Bed Material in Harris Creek. Water Resources Research 38, doi: 10.1029/2001 WR000753:19-1-19-12.

Church, M., M.A. Hassan and J.F. Wolcott, 1998. Stabilizing Self-Organized Structures in Gravel-Bed Stream Channels: Field and Experimental Observations. Water Resources Research 34:3169-3179.

Church, M. and J.M. Ryder, 2001. Watershed Processes in the Southern Interior of British Columbia: Background to Land Management. *In:* Watershed Assessment in the Southern Interior of British Columbia: Workshop Proceeding, D.A.A. Toews, and S. Chatwin (Editors). British Columbia Ministry of Forests, Working Paper 57, Victoria, B.C., Canada, pp. 1-16.

Costa, J.E., 1984. Physical Geomorphology of Debris Flows. *In:* Developments and Applications of Geomorphology, J.E. Costa and P.J. Fleisher (Editors). Springer, Berlin, Germany. pp.268-317.

Costa, J.E., 1988. Rheologic, Geomorphic, and Sedimentological Differentiation of Water Floods, Hyperconcentrated Flows, and Debris Flows. *In:* Flood Geomorphology, V.R. Baker, R.R.C. Kochel and P.C. Patton (Editors). John Wiley, New York, New York, pp. 113-122.

D'Agostino, V. and M.A. Lenzi, 1999. Bedload Transport in the Instrumented Catchment of Rio Cordon, Part II: Analysis of Bedload Rate. Catena 36:191-204.

DeJong, C., 1995. Temporal and Spatial Interactions Between River Bed Roughness, Geometry, Bedload Transport and Flow Hydraulics in Mountain Streams – Examples From Squaw Creek (Montana, USA) and Lainbach/Schmiedlaine (Upper Bavaria, Germany). Department of Geography. Free University Berlin, Heft 59, 229 pp.

DeVries, P.E., 1997. Riverine Salmonid Egg Burial Depths: Review of Published Data and Implications for Scour Studies. Canadian Journal of Fisheries and Aquatic Sciences 54:1685-1698.

DeVries, P.E., S.J. Burges and J. Daigneau, 2001. Measurements of the Temporal Progression of Scour in a Pool-Riffle Sequence in a Gravel Bed Stream Using an Electronic Scour Monitor. Water Resources Research 37:2805-2816.

Dietrich, W.E., J.W. Kirchner, H. Ikeda and F. Iseya, 1989. Sediment Supply and the Development of the Coarse Surface Layer in Gravel-Bedded Rivers. Nature 340:215-217.

Dunne, T., 2001. Introduction to Section 2: Problems in Measuring and Modeling the Influence of Forest Management on Hydrologic and Geomorphic Processes. *In:* Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban Forest Areas, M.S. Wigmosta and S.J. Burges (Editors). American Geophysical Union, Water Science and Application 2, American Geophysical Union, Washington, D.C., pp. 77-83.

Dyrness, C.T., 1970. Stabilization of Newly Constructed Road Backslopes by Mulch and Grass-Legume Treatment. USDA, Forest Service Research Note PNW-123, Pacific Northwest Forest and Range Experimental Station, Portland, Oregon.

Emmett, W.W., 1980. A Field Calibration of the Sediment Trapping Characteristics of the Helley-Smith Bedload Sampler. U.S. Geological Survey, Professional Paper 1139, Washington, D.C., 44 pp.

Emmett, W.W. and M.G. Wolman, 2001. Effective Discharge and Gravel-Bed Rivers. Earth Surface Processes and Landforms 26:1369-1380.

Ergenzinger, P. and S.G. Custer, 1983. Determination of Bedload Transport Using Naturally Magnetic Tracers: First Experiences at Squaw Creek, Gallatin County, Montana. Water Resources Research 19:187-193.

Fannin, R.J. and T.P. Rollerson, 1993. Debris Flows: Some Physical Characteristics and Behaviour. Canadian Geotechnical Journal 30:71-81.

Ferguson, R.I., 1994. Critical Discharge for Entrainment of Poorly Sorted Gravel. Earth Surface Processes and Landforms 19:179-186.

Fransen, P.J.B., C.J. Phillips, and B.D. Fahey, 2001. Forest Road Erosion in New Zealand: Overview. Earth Surface Processes and Landforms 26:165-174.

Gintz, D., M.A. Hassan, and K.H. Schmidt, 1996. Frequency and Magnitude of Bedload Transport in a Mountain River. Earth Surface Processes and Landforms 21:433-446.

Gomi, T., 2002. Dynamics of Sediment and Woody Debris in Headwater Streams, Southeast Alaska. Ph.D. Thesis, the University of British Columbia, Vancouver, British Columbia, Canada, 200 pp.

Gomi, T., R.D. Moore, and M.A. Hassan, 2005, Suspended Sediment Dynamics in Small Forest Streams on the Pacific Northwest. Journal of the American Water Resources Association (JAWRA) 41(4):877-898.

Gomi, T., R.C. Sidle, R.D. Woodsmith, and M.D. Bryant, 2003. Characteristics of Channel Steps and Reach Morphology in Headwater Streams, Southeast Alaska. Geomorphology 51:225-242.

Gottesfeld, A.S., 1998. Bedload Transport During Sockeye Redd Excavation and by Floods in the Stuart-Takla Experimental Watersheds, British Columbia. *In:* Proceeding of Forest-Fish Conference, Land Management Practices Affecting Aquatic Ecosystems, M.K. Brewin and D.M.A. Monita (Editors). Natural Resources Canada, Calgary, Alberta, Canada, pp. 249-258.

Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw Hill Book Co., New York, New York.

Grant, G.E., 1994. Hydraulics and Sediment Transport Dynamics Controlling Step-Pool Formation in High Gradient Streams: A Flume Experiment. *In:* Dynamics and Geomorphology of Mountain Rivers: Pre-Symposium Publication, K.H. Schmidt and P. Ergenzinger, (Editors). Springer-Verlag, Beneditbeuern, Germany, pp. 241-250.

Grant, G.E., M.J. Crozier, and F.J. Swanson, 1984. An Approach to the Evaluating Off-Site Effects of Timber Harvest Activities on Channel Morphology. *In:* Proceeding, Symposium on the Effects of Forest Land Use on Erosion and Slope Stability. Environment and Policy Institute, University of Hawaii, Honolulu, Hawaii, pp. 177-186.

Grant, G.E., F.J. Swanson, and M.G. Wolman, 1990. Pattern and Origin of Stepped-Bed Morphology in High Gradient Streams, Western Cascades, Oregon. Geological Society of America Bulletin 102:340-352.

Grant, G.E. and A.L. Wolff, 1991. Long-Term Patterns of Sediment Transport After Timber Harvest, Western Cascade Mountains, Oregon, USA. *In:* Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation. IAHS Publication No. 203, pp. 31-40.

Halwas, K.L. and M. Church, 2002. Channel Units in Small, High Gradient Streams on Vancouver Island, British Columbia. Geomorphology 43:243-256.

Haschenburger, J.K., 1999. A Probability Model of Scour and Fill Depths in Gravel-Bed Channels. Water Resources Research 35:2857-2869.

Haschenburger, J.K. and M. Church, 1998. Bed Material Transport Estimated From the Virtual Velocity of Sediment. Earth Surface Processes and Landforms 23:791-808.

Hassan, M.A., 1990. Scour, Fill, and Burial Depth of Coarse Material in Gravel Bed Streams. Earth Surface Processes and Landforms 15:341-356.

Hassan, M.A. and M. Church,1992. The Movement of Individual Grains on the Streambed. *In:* Dynamics of Gravel Bed Rivers, P. Billi, R.E. Hey, C.R. Thorne and P. Tacconi (Editors). Wiley, Chichester, United Kingdom, pp. 159-175.

Hassan, M.A. and M. Church, 1994. Vertical Mixing of Coarse Particles in Gravel Bed Rivers: A Kinematic Model. Water Resources Research 30:1173-1185.

Hassan M.A. and M. Church, 2000. Experiments on Surface Structure and Partial Sediment Transport on a Gravel Bed. Water Resources Research 36:1885-1895.

Hassan, M.A. and M. Church, 2001. Rating Bedload Transport in Harris Creek: Seasonal and Spatial Variation Over a Cobble-Gravel Bed. Water Resources Research 37:813-825.

Hassan, M.A. and P. Ergenzinger, 2003. Tracers in Fluvial Geomorphology. *In:* Tools in Fluvial Geomorphology, G.M. Kondolf and H. Piegay (Editors). John Wiley, Chichester, United Kingdom, pp. 397-423.

Hassan, M.A. and I. Reid, 1990. The Influence of Microform Bed Roughness Elements on Flow and Sediment Transport in Gravel Bed Rivers. Earth Surface Processes and Landforms 15:739-750.

Hassan, M.A. and R. Woodsmith, 2004. Bedload Transport in an Obstructed-Formed Pool in a Forested Gravel-Bed Stream. Geomorphology 58:203-221.

Hayward, J.A., 1980. Hydrology and Stream Sediments in a Mountain Catchment. Special Publication 17, Tussock Grasslands and Mountain Lands Institutes, Lincoln College, Canterbury, New Zealand, 236 pp.

Hawkins, C.P., J.L. Kershner, P.A. Bisson, M. Bryant, L. Decker, S.V. Gregory, D.A. McCullough, K. Overton, G. Reeves, R. Steedman, and M. Young, 1993. A Hierarchical Approach to Classifying Stream Habitat Features. Fisheries 18(6):3-12.

Helley, E.J. and W. Smith, 1971. The Development and Calibration of a Pressure Difference Bed Load Sampler. U.S. Geological Survey, Open File Report, Washington, D.C., 18 pp.

Hickin, E.J., 1984. Vegetation and River Channel Dynamics. Canadian Geographer 2:111-126.

Hogan, D.L., 1986. Stream Channel Morphology: Comparison of Logged and Unlogged Watersheds in the Queen Charlotte Islands. Master's Thesis, Department of Geography, University of British Columbia, Vancouver, B.C., Canada, 220 pp.

Hogan, D.L. and S.A. Bird, 1998. Classification and Assessment of Small Coastal Stream Channels. *In:* Proceeding of Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coast Research to Management Solutions, D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (Editors). British Columbia Ministry of Forests Research Program, Victoria, B.C., Canada, pp. 189-200.

Hogan, D.L., S.A. Bird, and M.A. Hassan, 1998. Spatial and Temporal Evolution of Small Coastal Gravel-Bed Streams: The Influence of Forest Management on Channel Morphology and Fish Habitat. *In:* Gravel-Bed Rivers in the Environment, P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley (Editors). Water Resources Publications, LLC, Highland Ranch, Colorado, pp. 365-392.

Hubbell, D.W., H.H. Stevens, J.V. Skinner, and J.P. Beverage, 1985. New Approach to Calibrating Bed Load Samplers. American Society of Civil Engineering. Journal of Hydraulic Engineering 111:677-694.

Hughes, R.M. and B. James, 1989. A Hydrological Regionalization of Streams in Victoria, Australia, With Implications for Stream

Ecology. Australian Journal of Marine and Freshwater Research 40:303-326.

Hungr, O., G.C. Morgan, and R. Kellerhals, 1984. Quantitative Analysis of Debris Torrent Hazards for Design of Remedial Measures. Canadian Geotechnical Journal 22:663-677.

Ikeda, H., 1975. On the Bed Configuration in Alluvial Channels: Their Types and Condition of Formation With Reference to Bars. Geographical Review of Japan 48:712-730.

Jackson, W.L. and R.L. Beschta, 1982. A Model of Two-Phase Bedload Transport in an Oregon Coast Range Stream. Earth Surface Processes and Landforms 7:517-527.

Jaeggi, M.N.R., 1995. Sediment Transport in Mountain Rivers – A Review. *In:* International Conference on Erosion Control. The Sabo Society of Japan, Tokyo, Japan (Keynote Address), 13 pp.

Jakob, M. and P. Jordan, 2001. Design Flood Estimates in Mountain Streams – The Need for a Geomorphic Approach. Canadian Journal of Civil Engineering 28:425-439.

Janda, R.J., K.M. Nolan, D.R. Harden, S.M. Colman, 1975. Watershed Conditions in the Drainage Basin of Redwood Creek, Humboldt County, California as of 1973. USGS, Open File Report 75-568, Washington, D.C.

Jones, H.R. and J.C. Peters, 1977. Physical and Biological Typing of Unpolluted Rivers. Technical Report TR 41, Medmenham Laboratory, Medmenham, United Kingdom.

Judd, H.E. and D.F. Peterson, 1969. Hydraulics of Large Bed Element Channels. Report Number PRWG 17-6, Utah Water Resources Laboratory, Utah State University, Logan, Utah, 115 pp.

Keller, E.A., 1971. Areal Sorting of Bedload Material: A Hypothesis of Velocity Reversal. Geological Society of America Bulletin 82:753-756.

Keller, E.A. A. MacDonald, and T. Tally, 1981. Streams in the Coastal Redwood Environment: The Role of the Large Organic Debris. *In:* Proceedings, Symposium on Watershed Rehabilitation in Redwood National Park and Other Coastal Areas, Binghamton, New York, R.N. Coates (Editor). Kendall/Hunt, Dubuque, Iowa, pp. 161-176.

Keller, E.A. and F.J. Swanson, 1979. Effects of Large Organic Material on Channel Form and Fluvial Processes. Earth Surface Processes 4:361-380.

Klingeman, P.C. and W.W. Emmett, 1982. Gravel Bedload Transport Processes. *In:* Gravel-Bed Rivers: Fluvial Processes, Engineering and Management, R.D. Hey, J.C. Bathurst, and C.R. Thornes (Editors). John Wiley, New York, New York, pp. 141-169.

Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, New York, New York.

Komar, P.D. and M.Z. Li, 1988. Application of Grain Pivoting and Sliding Analyses to Selective Entrainment of Gravel and to Flow Competence Evaluations. Sedimentology 35:681-695.

Kuhnle, R.A., 1992. Bedload Transport During Rising and Falling Stages on Two Small Streams. Earth Surface Processes and Landforms 17:191-197.

Lancaster, S.T., S.K. Hayes, and G.E. Grant, 2001. Modelling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds. *In:* Geomorphic Processes and Riverine Habitat, J.M. Dorava, D.R. Montgomery, B.B. Palcsak, and F.A. Fitzpatrick (Editors). American Geophysical Union, Water Science and Application 4, American Geophysical Union, Washington, D.C., pp. 85-102.

Lauffer, H. and N. Sommer, 1982. Studies on Sediment Transport in Mountain Streams of the Eastern Alps. *In:* Proc., International Commission on Large Dams, 14th Congress, Rio de Janiero. International Association for Hydraulic Research, Rio de Janeiro, Brazil, pp. 431-453.

Lenzi, M.A., V. D'Agostino, and P. Billi, 1999. Bedload Transport in the Instrumented Catchment of Rio Cordon, Part I: Analysis of Bedload Records, Conditions and Threshold of Bedload Entrainment. Catena 36:171-190.

Leopold, L.B., M.G. Wolman, and J.P. Miller, 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, California, 522 pp.

Likens, G.E. and R.E. Bilby, 1982. Development, Maintenance and Role of Organic Debris Dams in New England Streams. *In:* Sediment Budgets and Routing in Forested Drainage Basins, F.E. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (Editors). USDA Forest Service Research Paper PNW-141, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, pp. 122-128.

Lisle, T.E., 1986. Stabilization of a Gravel Channel by Large Streamside Obstructions and Bedrock Bends, Jacoby Creek, Northwestern California. Geological Society of America Bulletin 97:999-1011.

Lisle, T. E., 1989. Sediment Transport and Resulting Deposition in Spawning Gravels, North Coastal California. Water Resources Research 25:1303-1319.

Lisle, T.E., 1995. Particle Size Variation Between Bedload and Bed Material in Natural Gravel Bed Channels. Water Resources Research 31:1107-1118.

Lisle, T.E., Y. Cui, G. Parker, J.E. Pizzuto, and A.M. Dodd, 2001. The Dominance of Dispersion in the Evolution of Bed Material Waves in Gravel Bed Rivers. Earth Surface Processes and Landforms 26:1409-1420.

Lisle, T.E. and S. Hilton, 1992. The Volume of Fine Sediment in Pools: An Index of Sediment Supply in Gravel Bed Streams. Water Resources Bulletin 28:371-383.

Lisle, T.E., J.E. Pizzuto, H. Ikeda, F. Iseya, and Y. Kodama, 1997. Evolution of a Sediment Wave in an Experimental Channel. Water Resources Research 33:1971-1981.

Luce, C.H. and T.A. Black, 2001. Spatial and Temporal Patterns in Erosion From Forest Roads. *In:* Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban Forest Areas, M.S. Wigmosta and S.J. Burges (Editors). American Geophysical Union, Water Science and Application 2, American Geophysical Union, Washington, D.C., pp. 165-178.

Madej, M.A., 2001. Erosion and Sediment Delivery Following Removal of Forest Roads. Earth Surface Processes and Landforms 26:175-190.

Madej, M.A. and V. Ozaki, 1996. Channel Response to Sediment Wave Propagation and Movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21:911-927.

Madsen, S.W., 1995. Channel Response Associated With Predicted Water and Sediment Yield Increases in Northwest Montana. MS Thesis, Colorado State University, Fort Collins, Colorado, 230 pp.

Massong, T.M. and D.R. Montgomery, 2000. Influence of Sediment Supply, Lithology, and Wood Debris on the Distribution of Bedrock and Alluvial Channels. Geological Society of America Bulletin 112:591-599.

Meade, R.H., 1985. Wavelike Movement of Bedload Sediment, East Fork River, Wyoming. Environmental Geology and Water Sciences 7:215-255.

Megahan, W.F., 1982. Channel Sediment Storage Behind Obstructions in Forested Drainage Basins Draining the Granitic Bedrock of the Idaho batholith. *In:* Analysis of Coniferous Forest Ecosystems in the Western United States, R.L. Edmonds, (Editor). Hutchinson Ross, Pennsylvania, pp. 114-121.

Megahan, W.F. and G.L. Ketcheson, 1996. Predicting Downslope Travel of Grantic Sediments From Forest Roads in Idaho. Water Resources Bulletin 32:371-382.

Megahan, W.F. and W.J. Kidd, 1972. Impacts of Logging and Logging Roads on Erosion and Sediment Deposition in Steep Terrain. Journal of Forestry 7:136-141.

Megahan, W.F., K.A. Seyedbagheri, and P.C. Dodson, 1983. Long-Term Erosion on Granitic Roadcuts Based on Exposed Tree Roots. Earth Surface Processes and Landforms 8:19-28.

Meyer-Peter, E. and R. Muller, 1948. Formulas for Bedload Transport. *In:* Proc., Second Meeting, International Association for Hydraulic Structures Research, Stockholm, Sweden, Appendix 2, pp. 39-64.

Miles, M.J. and R. Kellerhals, 1981. Some Engineering Aspects of Debris Torrents. Proceedings, Fifth Canadian Hydrotechnical Conference, Fredericton, New Brunswick. The Canadian Society for Civil Engineering, Fredericton, New Brunswick, Canada, pp. 395-420.

Milhous, R.T., 1973. Sediment Transport in a Gravel-Bottomed Stream. PhD Thesis, Oregon State University, Corvallis, Oregon, 232 pp.

Miller, D.J. and L.E. Benda, 2000. Effects of Punctuated Sediment Supply on Valley-Floor Landforms and Sediment Transport. Geological Society of America Bulletin 112:1814-1824.

Mizuyama, T., 1977. Bedload Transport in Steep Channels. Ph.D. Thesis, Kyoto University, Kyoto, Japan, 118 pp.

Montgomery, D., 1994. Road Surface Drainage, Channel Initiation, and Slope Instability, Water Resources Research 30:1925-1932.

Montgomery, D.R., T.B. Abbe, J.M. Buffington, N.P. Peterson, K.M. Schmidt, and J.D. Stock, 1996b. Distribution of Bedrock and Alluvial Channels in Forested Mountain Drainage Basins. Nature 381:587-589.

Montgomery, D.R. and J.M. Buffington, 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Conditions. Report TFW-SH10-93-002, Washington State Dept. of Natural Resources, Olympia, Washington, 84 pp.

Montgomery, D.R. and J.M. Buffington, 1997. Channel Reach Morphology in Mountain Drainage Basins. Geological Society of America Bulletin 109:596-611.

Montgomery, D.R. and J.M. Buffington, 1998. Channel Processes, Classification, and Response. *In:* River Ecology and Management: Lesson From the Pacific Coastal Ecoregion, R.J. Naiman, and R.E. Bilby (Editors). Springer-Verlag, New York, New York, pp. 13-42.

Montgomery, D.R., J.M. Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn, 1996a. Stream-Bed Scour, Egg Burial Depth, and the Influence of Salmonid Spawning on Bed Surface Mobility and Embryo Survival. Canadian Journal of Fisheries and Aquatic Sciences 53:1061-1070.

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess, 1995. Pool Spacing in Forest Channels. Water Resources Research 31:1097-1105.

Montgomery, D.R. and W.E. Dietrich, 1988. Where Do Channels Begin? Nature 336:232-234.

Moog, D.B. and P.J. Whiting, 1998. Annual Hysteresis in Bedload Rating Curves. Water Resources Research 34:2393-2399.

Meyer, G.A., S.G. Wells, R.C. Balling, Jr., and A.J.T. Jull, 1992. Response of Alluvial Systems to Fire and Climate Change in Yellowstone National Park. Nature 357:147-150.

Myers, T. and S. Swanson, 1997. Variability of Pool Characteristics With Pool Type and Formative Feature on Small Great Basin Rangeland Streams. Journal of Hydrology 201:62-81.

Nakamura, F., F.J. Swanson, and S.M. Wondzell, 2000. Disturbance Regimes of Stream and Riparian Systems – A Disturbance-Cascade Perspective. Hydrological Processes 14:2849-2860.

Nanson, G. C., 1974. Bedload and Suspended-Load in a Small, Steep Mountainstream. American Journal of Science 274:471-486.

O'Connor, M.D., 1994. Sediment Transport in Steep Tributary Streams and the Influence of Large Organic Debris. Ph.D. Thesis, University of Washington, Seattle, Washington, 257 pp.

O'Loughlin, C.L., 1972. An Investigation of the Slope Stability of the Steepland Forest Soils in the Coast Mountains, Southwest British Columbia. PhD Thesis, University of British Columbia, Vancouver, British Columbia, 147 pp.

O'Loughlin, C.L., L.K. Rowe, and A.J. Pearce, 1978. Sediment Yields From Small Forested Catchments, North Westland-Nelson, New Zealand. Journal of Hydrology (New Zealand) 17:1-15.

Parker, G., S. Dhamotharan, and S. Stefan, 1982. Model Experiments on Mobile, Paved Gravel Bed Stream. Water Resources Research 18:1395-1408.

Parker, G. and P.C. Klingeman, 1982. On Why Gravel Bed Streams are Paved. Water Resources Research 18:1409-1423.

Paustian, S.J. and R.L. Beschta, 1979. The Suspended Sediment Regime of Oregon Coast Range Stream. Water Resources Bulletin 15:144-154.

Pearce A.J. and A. Watson, 1983. Medium-Term Effects of Two Landsliding Episodes on Channel Storage of Sediment. Earth Surface Processes and Landforms 8:29-39.

Poff, N.L. and J.V. Ward, 1989. Implications of Streamflow Variability and Predictability for Lotic Community Structure: A Regional Analysis of Streamflow Patterns. Canadian Journal of Fisheries and Aquatic Sciences 46:1805-1818.

Reid, I., A.C. Brayshaw, and L.E. Frostick, 1984. An Electromagnetic Device For Automatic Detection of Bedload Motion and Its Field Applications. Sedimentology 31:269-276.

Reid, I., L.E. Frostick, and J.L. Lyman, 1985. The Incidence and Nature of Bedload Transport During Flood Flows in Coarse-Grained Alluvial Channels. Earth Surface Processes and Landforms 10:33-44.

Reid, I. and J.B. Laronne, 1995. Bedload Sediment Transport in an Ephemeral Stream and a Comparison With Seasonal and Perennial Counterparts. Water Resources Research 31:773-781.

Reid, I., J.T. Layman, and L.E. Frostick, 1980. The Continuous Measurement of Bedload Discharge. Journal of Hydraulic Research 18:243-249.

Reid, L.M. and T. Dunne, 1984. Sediment Production From Forest Road Surfaces. Water Resources Research 20:1753-1761.

Reid, L.M., T. Dunne, and C.J. Cederholm, 1981. Application of Sediment Budget Studies to the Evaluation of Logging Road Impact. Journal of Hydrology 20:49-62.

Rice, S and M. Church, 1996. Bed Material Texture in Low Order Streams on the Queen Charlotte Islands, British Columbia. Earth Surface Processes and Landforms 21:1-18.

Rickenmann, D., 1990. Bedload Capacity of Slurry Flows at Steep Slopes. *In:* Mitteilung der Versuchsanstalt fur Wasserbau. Hydrologie und Glaziologie, Rep. 103, Eidg. Tech. Hochsch, Zurich, Zurich, Switzerland, 249 pp.

Rickenmann, D., 1992. Hyperconcentrated Flow and Sediment Transport at Steep Slopes. Journal of Hydraulic Engineering 117:1419-1439.

Rickenmann, D., 2001. Comparison of Bedload Transport in Torrents and Gravel Bed Streams. Water Resources Research 37:3295-3305.

Riley, S.J., 1988. Soil Loss From Road Batters in the Karuah State Forest, Eastern Australia. Soil Technology 1:313-332.

Roberts, R.J. and M. Church, 1986. The Sediment Budget in Severely Disturbed Watersheds, Queen Charlotte Ranges, British Columbia. Canadian Journal of Earth Sciences 16:1092-1106.

Rollerson, T.P., 1992. Relationships Between Landscape Attributes and Landslide Frequencies After Logging: Skidegate Plateau, Queen Charlotte Islands, British Columbia Ministry of Forests, Victoria, British Columbia, 11 pp.

Rood, K. M., 1984. An Aerial Photograph Inventory of the Frequency and Yield of Masswasting on the Queen Charlotte Islands, British Columbia. Land Management Report No.34, British Columbia Ministry of Forests, Victoria, British Columbia, 55 pp.

Rood, K.M., 1990. Site Characteristics and Landsliding in Forested and Clearcut Terrain, Queen Charlotte Islands, British Columbia. Land Management Report No. 64, British Columbia Ministry of Forests, Victoria, British Columbia, 46 pp.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22:169-199.

Ryan, S.E., 1994. Bedload Transport Pattern in Pool-Riffle and Step-Pool Stream Systems. *In:* Effects of Human-Induced Changes on Hydrologic Systems, Richard A. Marston and Victor Hasfurther (Editors). American Water Resources Association, TPS-94-3, pp. 669-678.

Ryan, S.E., 1997. Morphologic Response of Subalpine Streams to Transbasin Flow Diversion. Journal of the American Water Resources Association (JAWRA) 33(4):839-854.

Ryan, S.E., 2001. The Influence of Sediment Supply on Rates of Bed Load Transport: A Case Study of Three Streams on the San Juan National Forest. Proceeding of the Seventh Federal Interagency Sedimentation Conference, Reno, Nevada. U.S. Dept. of the Interior, Bureau of Land Management, Washington, D.C., pp. III-48-III-54.

Ryan, S.E. and W.W. Emmett, 2002. The Nature of Flow and Sediment Movement in Little Granite Creek Near Bondurant, Wyoming. General Technical Report RMRS-GTR-90, Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 48 pp.

Ryan, S.E. and C.A. Troendle, 1996. Bed Load Transport Patterns in Coarse-Grained Channels Under Varying Conditions of Flows. *In:* Sedimentation Technologies for Management of Natural Resources in the 21st Century. Proceeding of the Sixth Federal Interagency Sedimentation Conference, Las Vegas, Nevada. Water Resources Council, Vol. 2, pp. VI-22-VI-27.

Ryan, S.E. and C.A. Troendle, 1997. Measuring Bedload in Coarse-Grained Mountain Channels Procedures, Problems, and Recommendations. *In:* Water Resources Education, Training, and Practice: Opportunities for the Next Century, J.J. Warwick (Editor). American Water Resources Association, TPS-97-1, pp. 949-958.

Sauder, E.A., R.K. Krag, and G.V. Wellburn, 1987. Logging and Mass Wasting in the Pacific Northwest With Application to the Queen Charlotte Islands, B.C. Land Management Report No. 53, British Columbia Ministry of Forests, Victoria, British Columbia, 26 pp.

Sawada, T., K. Ashida, and T. Takahashi, 1983. Relationship Between Channel Pattern and Sediment Transport in a Steep Gravel Bed River. Z. Geomorph, N.F. Suppl. Bd. 16, pp. 55-66.

Schoklitsch, A., 1962. Handbuch des Wasserbaues (Third Edition). Springer-Verlag, Vienna, Austria.

Schwab, J.W., 1983. Mass Wasting: October-November 1978 Storm, Rennell Sound, Queen Charlotte Islands, British Columbia. Land Management Report No. 91, British Columbia Ministry of Forests and Lands, Victoria, British Columbia, 23 pp.

Shields, A., 1936. Andwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. (Application of the Theory of Similarity and Turbulence Research to the Bedload Movement: translated by Q.M. Saleh). Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, 26, Berlin, Germany.

Sidle, R.C., 1988. Bedload Transport Regime of a Small Forested Stream. Water Resources Research 24:207-218.

Sidle, R.C., A.J. Pearce, and C.L. O'Loughlin, 1985. Hillslope Stability and Landuse. American Geophysical Union, Washington, D.C., Water Resources Monographs 11, 140 pp.

Slaymaker, O., 1993. The Sediment Budget of the Lillooet River Basin, British Columbia. Physical Geography14:304-320.

Slaymaker, O., 2000. Assessment of the Geomorphic Impacts of Forestry in British Columbia. Ambio 29:381-387.

Smart, G.M. and M.N.R. Jaeggi, 1983. Sediment Transport on Steep Slopes. Mitteilung der Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie, ETH Zurich, Nr. 64. 191 pp.

Smith, R.D., R.C. Sidle, and P.E. Porter, 1993a. Effects on Bedload Transport of Experimental Removal of Woody Debris From a Forest Gravel-Bed Stream. Earth Surface Processes and Landforms 18:455-468.

Smith, R.D., R.C. Sidle, P.E. Porter, and J.R. Noel, 1993b. Effects of Experimental Removal of Woody Debris on the Channel Morphology of a Forest, Gravel Bed Stream. Journal of Hydrology 152:153-178.

Solari, L. and G. Parker, 2000. The Curious Case of Mobility Reversal in Sediment Mixtures. Journal of Hydraulic Engineering 126:185-197.

Sterling, S. and M. Church, 2002. Sediment Trapping Characteristics of a Pit Trap and a Helley-Smith Sampler in a Cobble-Gravel Bed River. Water Resources Research 38(8):19-1-19-11, doi: 10.1029/2000WR000052.

Sullivan, K., 1986. Hydraulics and Fish Habitat in Relation to Channel Morphology. Ph.D. Dissertation, The Johns Hopkins University, Baltimore, Maryland, 407 pp.

Sutherland, D.G., M.H. Ball, S.J. Hilton, and T.E. Lisle, 2002. Evolution of a Landslide-Induced Sediment Wave in the Navarro River, California. Geological Society of America Bulletin 114:1036-1048.

Swanson, F.J., 1981. Fire and Geomorphic Processes. U.S. Department of Agriculture, Forest Service, General Technical Report WO26, Washington, D.C., pp. 401-420.

Swanson, F.J., S.V. Gregory, J.R. Sedell, and A.G. Campbell, 1982c. Land-Water Interactions: The Riparian Zone. *In:* Analysis of Coniferous Forest Ecosystems in the Western United States, R.L. Edmonds (Editor). Hutchinson Ross, Pennsylvania, pp. 267-291.

Swanson, F.J., R.J. Janda, and T. Dunne, 1982b. Summary: Sediment Budgets and Routing in Forested Drainage Basins. *In:* Sediment Budgets and Routing in Forested Drainage Basins, F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (Editors). U.S. Department of Agriculture, General Technical Report Number PNW-141, Portland, Oregon, pp. 157-165.

Swanson, F.J., R.J. Janda, T. Dunne, and D.N. Swanston (Editors), 1982a. Sediment Budgets and Routing in Forested Drainage Basins. U.S. Department of Agriculture, Forest Service, General Technical Report PNW-141, Portland, Oregon, 165 pp.

Swanston, D.N. and F.J. Swanson, 1976. Timber Harvesting, Mass Erosion and Steepland Forest Geomorphology in the Pacific Northwest. *In:* Geomorphology and Engineering, D.R. Coates (Editor). Allen and Unwin, New York, New York, pp.199-221.

Tinkler, K.J. and E.E. Wohl (Editors), 1998. Rivers Over Rock. Geophysical Monograph, 107, American Geophysical Union, Washington, D.C., 323 pp.

Troendle, C.A., J.M. Nankervis, and S.E. Ryan, 1996. Sediment Transport From Small, Steep-Gradient Watersheds in Colorado and Wyoming. *In:* Sedimentation Technologies for Management of Natural Resources in the 21st Century. Proceeding of the Sixth Federal Interagency Sedimentation Conference, Las Vegas, Nevada. Water Resources Council, Vol. 2, pp. IX-39-IX-45.

Tunnicliffe, J., A.S. Gottesfeld, and M. Mohamed, 2000. High Resolution Measurement of Bedload Transport. Hydrological Processes 14:2631-2643.

Warburton, J., 1992. Observation of Bedload Transport and Channel Bed Changes in a Proglacial Mountain Stream. Arctic and Alpine Research 24:195-203.

Wemple, B.C., F.J. Swanson, and J.A. Jones, 2001. Forest Roads and Geomorphic Process Interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms 26:191-204.

Whiting, P.J. and J.B. Bradley, 1993. A Process Based Classification System for Headwater Streams. Earth Surface Processes and Landforms 18:603-612.

Whittaker, J.G., 1987. Sediment Transport in Step-Pool Streams. *In:* Sediment Transport in Gravel-Bed Rivers, C.R. Thorne, J.C. Bathurst, and R.D. Hey (Editors). Wiley and Sons, Chichester, United Kingdom, pp. 545-579.

Wilcock, P.R. and B.W. McArdell, 1993. Surface-Based Fractional Transport Rates: Mobilization Thresholds and Partial Transport of a Sand-Gravel Sediment. Water Resources Research 29:1297-1312.

Wilcock, P.R. and B.W. McArdell, 1997. Partial Transport of a Sand/Gravel Sediment. Water Resources Research 33:235-245.

Williams, G.P., 1989. Sediment Concentration Versus Water Discharge During Single Hydrologic Events in Rivers. Journal of Hydrology 111:89-106.

Wohl, E.E., 2000. Mountain Rivers. American Geophysical Union, Washington, D.C., Water Resources Monographs 14, 320 pp.

Wohl, E.E., K.R. Vincent, and D.J. Merritts, 1993. Pool and Riffle Characteristics in Relations to Channel Gradient. Geomorphology 6:99-110.

Zimmerman, A. and M. Church, 2001. Channel Morphology, Gradient Profiles and Bed Stresses During Spring Runoff in a Step-Pool Channel. Geomorphology 40:311-328.