

**EFFECTS OF HYDRAULIC ROUGHNESS AND SEDIMENT SUPPLY ON
SURFACE TEXTURES OF GRAVEL-BEDDED RIVERS**

By

John M. Buffington



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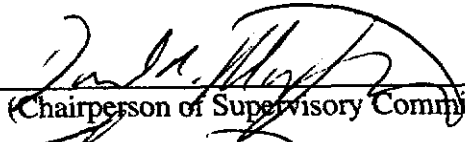
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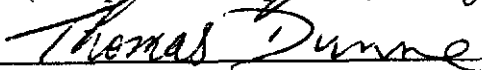
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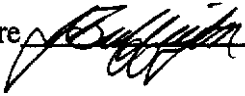
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Abstract

Effects of Hydraulic Roughness and Sediment Supply on Surface Textures
of Gravel-bedded Rivers

by John M. Buffington

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Textural response to sediment supply and other hydraulic roughness elements in gravel-bedded rivers is examined by comparing reach-average median surface grain sizes (D_{50s}) with those predicted from a simple threshold channel model. An extensive literature review of **bedload** transport studies indicates that sediment transport in gravel-bedded channels is to a **first** approximation **bankfull** threshold. Using Shields' equation D_{50s} is predicted from **bankfull** depth and slope, providing a theoretical reference point for examining textural response. The model, however, requires specification of a dimensionless critical shear stress parameter (τ^*_{c50s}), which is made uncertain by the current state of the incipient motion literature. A detailed review of this literature demonstrates distinct methodological biases in previously reported results (commonly assumed, but poorly documented) and it is **concluded that** of the τ^*_{c50s} values currently available 0.032 is the most appropriate for **natural** channels.

Previously documented textural response to sediment supply is examined within the bankfull-threshold framework, showing that increased sediment loading causes a systematic textural fining and deviation from model predictions. Textural response to **bedform** and large woody debris (**LWD**) roughness is investigated through a field study of gravel-bedded channels in forest environments of western Washington and southeast Alaska. Surface textures are examined in three distinctly different channel morphologies representing an increasing complexity of channel roughness: plane-bed, LWD-poor **pool-riffle**, and LWD-rich pool-riffle. Results show that textural fining in response to hydraulic roughness features occurs at both reach and **local** scales and that the number and spatial complexity of textural patches increases with greater complexity of channel roughness. Within the bankfull-threshold framework, reach-average median surface grain sizes segregate by channel type into distinct zones of textural response, **with** plane-bed channels

showing the least deviation from model predictions and LWD-rich pool-riffle **channels** the most. Median **values** of textural response distributions reveal that roughness caused by **bedforms** and minimal LWD result in a **two-and-half-fold** decrease in **D_{50s}** relative to model predictions, while pool-riffle channels with abundant LWD exhibit a four-and-a-half-fold decrease.

In the channels studied, non-catastrophic levels of sediment loading are apparently subordinate to the controls on surface texture caused by **bedform** and LWD roughness. Although there is the potential for severe sediment impacts (and hence sediment-induced textural fining) in the study areas, such occurrences tend to be infrequent pulsed events compared to the pervasive influence of stable **bedforms** and LWD. Consequently, **bedforms** and LWD provide long term influences that dominate surface textures of the study sites, while sediment supply effects are either relatively less **significant** or transient.

Coupled with subsurface grain size sampling, the bankfull-threshold model allows evaluation of the degree of textural fining within theoretical grain size limits and is proposed as a management tool for assessing channel textural-response condition. Naturally large degrees of textural fining in LWD-rich **pool-riffle** channels generally correspond with small capacities for further surface fining. The bankfull-threshold model and empirically determined response ranges also offer an opportunity to examine geomorphic controls on the availability of **salmonid** spawning gravels. Textural **fining** due to sediment supply and hydraulic roughness elements significantly increases spawning habitat availability.

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INTRODUCTION

A rising **environmental** consciousness coupled with an acceleration in the rate of land development and timber harvesting in North America have created a need for a better **understanding** of physical and biologic processes in watersheds. River channels integrate the effect of watershed processes, and as such provide an expression of basin condition. Thus a better understanding of river processes is of particular importance for both interpreting watershed condition and assessing potential land use impacts to human and animal uses of a watershed.

Successful development and application of any form of channel assessment requires a process-based understanding of **fluvial** systems. State and federal agencies are developing process-based watershed analysis programs (**FEMAT**, 1993; **WFPB**, 1993; USDA, 1994) and are currently investigating some of the available channel assessment techniques [see review in Montgomery and **Buffington (1993)**]. Bed surface textures are an important characteristic of rivers, and several assessment methods rely on textural analysis as an indicator of channel processes and condition (e.g., **Dietrich et al.**, 1989; Lisle and Hilton, 1992; Kappesser, 1993).

Based on the premise that surface textures are responsive to and indicative of shear stress, sediment supply, and the presence of other roughness elements, I propose and investigate the use of a simple threshold-channel model that allows prediction of **surface** grain size from **bankfull shear** stress and provides a theoretical reference point from which to analyze textural response to sediment supply and hydraulic roughness. Textural response to sediment supply has been documented by several researchers (i.e., **Dietrich et al.**, 1989), however response to hydraulic roughness, particularly in forest environments, has not been well studied. Textural response to **both** sediment supply and other hydraulic roughness is examined within the model framework through analysis of published data, as

well **as** through a **field** investigation that documents surface texture characteristics in **gravel-**bedded channels exemplifying different scales and complexity of roughness.

Implications of this work have several direct applications to land management concerns. A better understanding of 1) the factors that control streambed textures and 2) the characteristic ranges of textural response to these factors will aid assessment of channel condition and prediction of channel response to natural and anthropogenic disturbances. Combined with subsurface grain **size** measurements, the bankfull-threshold model is proposed as a management tool for evaluating both the general textural-response condition of a **channel** and its capacity for further response; use of the bankfull-threshold model in this fashion is essentially an extension of the **q*** technique (Dietrich et al., 1989) for assessing the sediment supply of a channel relative to its transport capacity. Finally, empirical findings of the **current study** are used to examine the geomorphic controls on availability of **salmonid** spawning habitat.

Chapter 1: The **Bankfull** Threshold **Model**

THRESHOLD CHANNEL CONCEPT

It is commonly observed that there are differences between sediment transport characteristics and **bedform** stability in fine-grained and coarse-grained channels. **Fine-grained** channels transport sediment at **almost** all stages and adjust their bed morphology to changing hydraulic regimes, whereas coarse-grained channels exhibit relatively stable **bedforms** and generally transport significant amounts of sediment only beyond some critical discharge. Thus there is a basic dichotomy between what are termed "**live-bed**" and "threshold" channels (Henderson, 1966; Parker 1978a; **b**; Howard, 1980). Live-bed streams have also been termed "regime" channels (Henderson, 1961; Howard, 1980), although, Inglis (1961) warns against such usage, as it befuddles Lindley's (1919) concept of "in regime". A channel is said to be "in regime" when it exhibits a stable morphologic state for the imposed sediment supply and hydraulic discharge (**Lacey**, 1961); as such, the regime concept can be applied to any alluvial channel type.

The term "threshold channel" was coined by Henderson (1963) and refers to **Lane's** (1953; 1955) examination of engineering designs aimed at producing "stable channels" in coarse alluvium. A stable channel was defined by Lane (1953) as an ". . . earth channel for carrying water, the banks **and** bed of which are not scoured by the moving water, and in which objectionable deposits of sediment do not occur." The point of this design is to engineer a channel which will neither degrade through scour nor be incompetent to carry the imposed sediment load, which would otherwise lead to deposition and aggradation within the channel. Lane proposed that an analysis of tractive forces could be used to determine the minimum bed material size that would be stable for a given channel geometry, slope, and discharge. As Henderson (1963) later points out, Lane's analysis

examines bed material at the "**threshold**" of mobility for given hydraulic geometry conditions.

Henderson (1963) examined differences in hydraulic geometry relations between threshold and live-bed channels and used Lane's tractive force model to approximate sediment mobility conditions in natural coarse-grained channels. Henderson reasoned that **the** threshold for mobility in coarse-grained channels was that of the dominant or **channel-forming** discharge, which based on considerations of channel morphology was interpreted to be the **bankfull** flow (Wolman and Leopold, 1957). However, it is not readily obvious that **bankfull** stage, as opposed to some other moderate discharge, is the threshold stage for grain mobilization. For example, live-bed channels also have a characteristic **bankfull** morphology, yet these channels do not exhibit a **bankfull** threshold for grain mobility. Nevertheless, it does seem reasonable that the critical **grain-mobilizing** stage for **coarse-grained** channels should lie somewhere within the limits of moderate to **bankfull** flow; this follows both from observation of little to no transport at low flows and from recognition **that** channels **with** well-developed floodplain morphology limit the effectiveness of flows beyond the **bankfull** stage (Henderson, 1963; Leopold et al., 1964; Andrews and Erman, 1986). While arguments for using **bankfull** stage to characterize channel- and bed-forming conditions are intuitively attractive (e.g., Wolman and Leopold, 1957; Henderson, 1963; Li et al., 1976), it remains to **justify** them. As such, I **will** briefly **summarize** some of the pertinent literature in order to examine the validity and limits of **bankfull** threshold representation of sediment transport in coarse-grained channels.

A further complicating issue not discussed above is the assertion by some investigators that sediment transport in heterogeneous **coarse-grained** channels is characterized by stage-dependent selective transport (Gilbert, 1914; Day, 1976; Little and Mayer, 1976; Proffit, 1980; Komar, 1987a; b; Rakoczi, 1987; Komar and Li, 1988; Wilcock and McArdell, 1993) rather than by threshold mobility at a single stage. Selective

transport is an important process and does occur in gravel-bedded channels due to effects of grain hiding (relative protrusion), imbrication, and friction angle **distributions** (a function of grain size, packing, and sorting) (**Li** and Komar, 1986; Kirchner et al., 1990, and **Buffington** et al., 1992). Selective transport must indeed occur to produce armored bed surfaces that are typical of most gravel-bedded streams. However, bed armoring is due to selective removal of the most easily mobilized grains (i.e., those of small **size** with high protrusion and low friction angle) leaving behind a more stable, armored bed surface that inhibits further **significant** grain transport, protecting the underlying, **finer** subsurface material (**Milhous**, 1973). Significant **bedload** transport occurs with the breaching of the armor surface, which as will be demonstrated below is typically a bankfull-threshold phenomenon. Consequently, *to a first approximation* sediment transport in coarse-bedded rivers can **be** considered **bankfull** threshold. This viewpoint is reinforced in the following literature review.

EVIDENCE OF BANKFULL THRESHOLD MOBILITY

Wolman and Miller (1960) examined the frequency and magnitude of geomorphic forces and proposed that both the effective discharge, that which accomplishes the most work of sediment transport, and the channel-forming discharge are equivalent frequent occurrences characterized by the **bankfull** flow [see also Wolman and Leopold (1957)]. In a subsequent study Andrews (1980) substantiated Wolman and **Miller's** concept of effective discharge and correlated it with near-bankfull stages. Although these studies demonstrate that **bankfull** stage is identified with both the channel-forming and **sediment-**transporting flows, it is not clear that **bankfull** is the threshold discharge for incipient motion.

Carling (1988) examined effective discharges and entrainment thresholds in two gravel-bedded channels. Over a six year period the effective discharges for the two channels were on average 94% and 100% **bankfull** respectively, **further** substantiating **Wolman** and Miller's (1960) findings. Furthermore, Carling observed three phases of grain mobility: phase 1 transport (discharge \leq 60% bankfull) characterized movement of **fine** material (< 4 mm) winnowed from the coarser framework (armor); phase 2 transport (>60% bankfull) represented threshold mobility of the coarse surface layer and entrainment of small framework gravels, but without significant exposure of subsurface material; and phase 3 transport (>130% bankfull) characterized extreme mobility of the coarse surface layer, significant scour, and the potential for major morphologic change. Discharges that significantly **modified** the coarse surface layer averaged 75% and 94% **bankfull** in the two study sites (Carling, 1987). These observations demonstrate the threshold nature (> 60% bankfull) of mobility of the coarse surface layer. Furthermore, while the mobilization of the coarse surface layer occurs over a range of discharges (60-130% bankfull), the **bankfull** stage can be considered a first-order approximation of the threshold discharge for significant bed mobility in these channels. Carling (1988) argues that the near-bankfull flow is dominant in terms of transporting **bedload** and maintaining channel form, while the catastrophic phase 3 transport is responsible for major but infrequent channel changes; similar ideas **were** expressed by **Wolman** and Miller (1960). **Carling** also presents evidence suggesting that the equivalence of sediment-transporting and **channel-forming** flows occurs only for channels that have achieved steady-state conditions [see also Richards (1982)].

Other investigators have **also** noted phases of **bedload** transport (Bathurst, 1987b) and a **near-bankfull** flow threshold for significant grain mobility in coarse-bedded channels. In a study of **bedload** transport in an armored gravel-bedded **stream** in coastal Oregon Milhous (1973) reported that "**bed** material is essentially stable during all but the highest flows." He observed that at low flows only exposed sand-sized material was transported,

while above a critical discharge of about 40 cfs the armor layer mobilized, exposing finer substrate and rapidly increasing both the rate of **bedload** transport and the size of **bedload** material [see also Parker et al. (1982a)]. Furthermore, he suggested that the armor layer effectively limits the availability of fines below this critical stage. Milhous estimated that 98% of the sediment transport occurs during flows in excess of 40 cfs. On a duration curve these flows occur about 3% of the time each year, which is within the **range** of other reported **bankfull** durations (Andrews, 1980; 1984). Milhous' observations exemplify **bankfull** threshold conditions.

In a separate study of another coastal Oregon stream Jackson and Beschta (1982) noted two similar grain mobility thresholds. Phase I transport is characterized by low-flow movement of sand-sized material over a stable armor, and Phase II transport, occurring at 108% bankfull, represents high-flow mobilization of the armor surface and a rapid rise in **bedload transport**. Again, demonstrating a **near-bankfull** threshold for **significant** mobility. In this case, transport rates continued to increase beyond the **bankfull** threshold, presumably because of channel confinement. Many other researchers also report rapid increases in **bedload** size and transport rate associated with high-flow **mobilization** of bed armor (Emmett, 1984, **Ashida**, 1981; Gomez, 1983; **Sawada** et al., 1983; Sidle, 1988; **Ashworth** and Ferguson, 1989; Warburton, 1992), emphasizing the characteristic quality of threshold mobility in coarse-bedded channels.

In contrast to the above investigations, Reid et al. (1985) found no clear relation between stage and **bedload** movement in a study of Turkey Brook, a gravel-bedded channel in England. They argue that **bedload** transport in Turkey Brook is a function of both kinematic wave phenomena (**Langbein** and Leopold, 1968) and the degree of bed "conditioning" by antecedent flow events. Conditioning refers to the packing, imbrication, and degree of armoring as controlled by the preceding discharge history (magnitude, frequency, duration, and chronologic order of events) and seasonal sediment inputs

(Nanson, 1974; Milhous, 1973; Griffiths, 1980; Jackson and Beschta, 1982; Campbell and Sidle, 1985; Bathurst, 1987b; Sidle, 1988). However, Reid et al. (1985) report significant **transport** during most flows observed, even though the largest flow attains a depth of only 70% bankfull, and the average recorded flood depth for all storms presented is less than 4.0% **bankfull**; significant **bedload** transport under these flow conditions is suggestive of live-bed transport. It is my opinion that the high **transport** rates that accompany these low flows are the result of high sediment loading. Dietrich et al. (1989) suggested that the closer the surface and subsurface median grain sizes (D_{50s} and D_{50ss}) are to one another, the higher the sediment loading. D_{50s} and D_{50ss} in Turkey Brook are 22 and 16 mm respectively, indicating only weak armoring and suggesting a fairly high sediment supply relative to transport capacity. In general, streams with high sediment **loading** typically behave more like live-bed channels than threshold channels, and Turkey Brook appears to demonstrate this.

Studies of Bambi Creek in southeast Alaska show an exponential **transport-discharge** relation, but do not clearly document a **bankfull** threshold of bed mobility (Campbell and Sidle, 1985; Sidle, 1988; Smith et al., 1993). The channel is armored and it is observed that fine (< 1 mm) material moves more frequently than coarse (> 8 mm) material (Sidle, 1988), suggesting that the coarse surface layer functions similarly to other armored channels **and** limits the availability of fine material below armor-mobilizing thresholds. However, Bambi Creek exhibits extreme **variability** in transport rates between and within storms and it is unclear if there is a single threshold for mobilization of the coarse surface layer. Transport variability is attributed to bed conditioning by antecedent flow events and to capacitance of morphologic sediment storage sites (pools and woody debris-butressed reservoirs) (Sidle, 1988).

A variety of other studies also provide information regarding the threshold nature of sediment transport in coarse-grained channels. Leopold et al. (1964) observed that over a

seven year period in Seneca Creek transport of bar-forming material occurs at discharges **near bankfull** stage; sand-sized material is **virtually** immobile at or below mean flow heights. Andrews (1983; 1984) calculated that in twenty-four Colorado rivers the threshold for grain mobility occurs at stages “slightly less than **bankfull**.” Based on the predicted and calculated critical dimensionless shear stress values presented by Andrews (1984) I calculate that on average grain mobility occurs at stages that are approximately 70% bankfull. Similar calculations for **Sagehen** Creek in northern California indicate a mobility threshold of 93% **bankfull** (Andrews and **Erman**, 1986). Using data from Lane and **Carlson** (1953), Kellerhals (1967) found a clear relation between observed **D_{50s}** and the boundary shear stress associated with the “maximum sustained discharge” [i.e., **bankfull** discharge (Andrews, 1984)]. In a tracer study of a coarse-grained river in northern California, Helley (1969) determined that the critical mobilizing stage occurs 5% of the time (based on mean monthly discharge records). Although 5% is a frequent event, it is well within the range of typical **bankfull** durations (0.12-6.0%) reported by Andrews (1984).

The weight of evidence in the literature summary presented above indicates that to a fit approximation coarse-grained channels are **bankfull** threshold. This conclusion will be used in the model formulation presented in the next section. However, it is recognized that a **bankfull** threshold theory is only a useful approximation of the complex nature of bed mobility in coarse-grained channels.

BANKFULL THRESHOLD MODEL

A major premise of this study is that bed surface textures are responsive to, **and** thus indicative of, shear stress, sediment supply, and the presence of other hydraulic roughness elements within a channel. Consequently surface textures can be used as

indicators of channel condition with respect to these factors, provided that the potential range of textural response to each factor is known and that the process-driven mechanics of textural response are understood.

Calculation of flow competence from surface grain sizes is a classic use of textures as indicators of current or past **fluvial** conditions. Equations of flow competence are commonly used to predict the critical mobilizing shear stress for a given grain size of interest (Helley, 1969; Baker and **Ritter**, 1975; Church, 1978; Bradley and **Mears**, 1980). In contrast, the **bankfull** threshold model utilized here predicts grain size based on the hypothesis that the **bankfull** boundary shear **stress** provides the critical tractive force for general incipient motion of the bed. By adopting a simplistic prediction of grain size the model provides a theoretical reference point from which **to-analyze** textural response to sediment supply and hydraulic roughness elements other than bed surface grains. Textural response within the **bankfull** threshold model framework can be quantified by the magnitude of deviation from the theoretical grain **size** prediction. Recognition and quantification of textural response caused by a specific process provides **valuable** channel assessment information. Derivation of the model and textural response hypotheses are examined in the remainder of this chapter.

In the absence of other influences the critical grain-mobilizing shear stress, τ_c , in a **bankfull** threshold channel can be characterized by the mean total **bankfull** boundary shear stress, τ_0

$$\tau_0 = \tau_c = \rho ghS \quad (1)$$

where p is the fluid density, g is the gravitational acceleration, h is the average **bankfull** flow depth, and S is the energy slope. The above expression for total boundary shear stress assumes steady incompressible flow, but can be used to describe either uniform or

non-uniform flow (Henderson, 1966). Equation (1) is a time-averaged representation of the channel shear stress, best applied on a reach scale.

At the **bankfull** threshold there is general **mobilization** of most size fractions on the bed. The phenomenon of general motion is attributed to the effects of both armoring and physical interactions of heterogeneous grains. Mobilization of armor particles releases finer material trapped under and around the coarser armor grains, resulting in a sudden entrainment of numerous sizes and giving rise to the observation of general motion (Fig. 1.1). In addition, because of grain interactions caused by the **natural** heterogeneity of bed surface material, the coarse surface layer tends to exhibit equal grain mobility (Parker and Klingeman, 1982), at least initially (Buffington et al., 1992), resulting in general motion of the bed at a common threshold shear stress. Grain interactions caused by the size, sorting, **shape**, and packing of bed material control physical features of the bed, such as friction angles and grain protrusion (Fig. 1.2), which dictate relative entrainment thresholds for bed surface grains (Fenton and Abbott, 1977; Kirchner et al., 1990). Friction angles cause bed surfaces to be relatively rougher for small grains and smoother for large grains (Fig. 1.2), resulting in an initial near-equal mobility of bed surface material at a common critical shear stress. However, the bed is rarely mobilized en masse, and due to friction angle controls strict equal mobility may only occur for the first **1-10%** of mobilized grains, after which selective transport may become increasingly important (Kirchner et al., 1990; Buffington et al., 1992). Nevertheless, bed mobility as indicated by friction angle distributions corroborates observations that beyond threshold conditions there is a general and significant mobility of grains, as evidenced by the well-known rapid rise in **bedload** transport.

Due to the grain interactions discussed above, mobility of the median surface grain size, D_{50s} , will be used in this analysis to **approximate** incipient motion of the bed as a

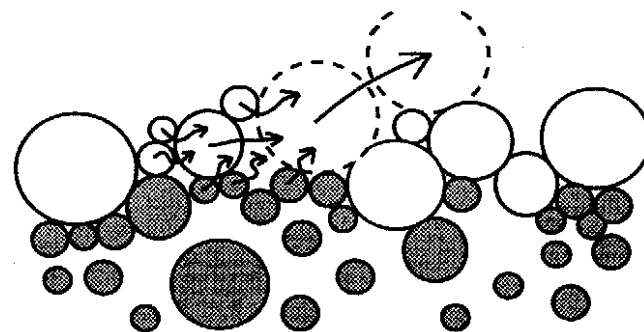
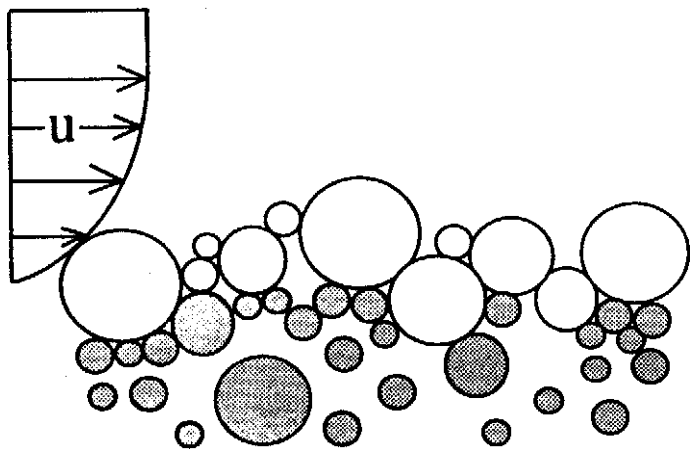


Figure 1.1 Movement of the arm part releases finer material
 entrainment of numerous grains at the bottom

and behind the grain, resulting in

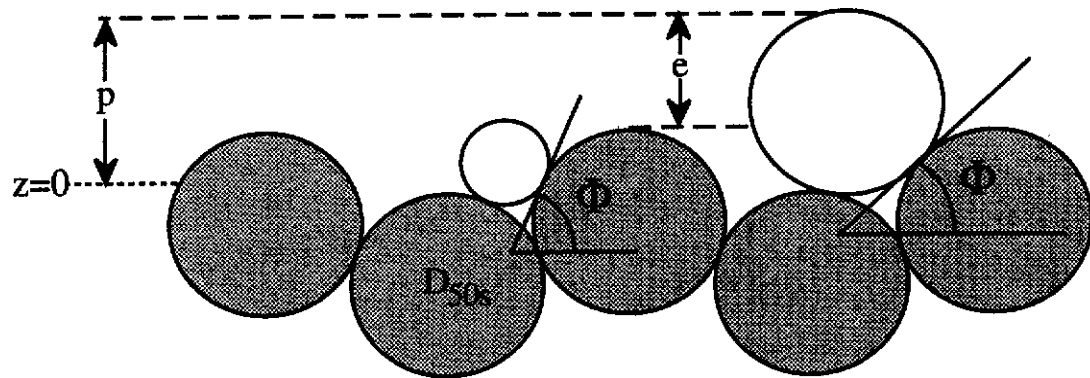


Figure 1.2 Friction angle, Φ , and relative grain protrusion, $p-e$, for two different grain sizes on a uniform streambed surface. Larger grains typically have lower friction angles and protrude higher into the flow than smaller grains, resulting in an initial near-equal mobility of different grain sizes at a common critical shear stress (Kirchner, 1990; Buffington et al., 1992).

whole. The median surface grain size can be related to its critical boundary shear stress, τ_{c50s} , through Shields' (1936) expression for dimensionless critical shear stress

$$\tau^*_{c50s} = \left(\frac{\tau_{c50s}}{(\rho_s - \rho) g D_{50s}} \right) \quad (2)$$

where τ^*_{c50s} is the dimensionless critical shear stress for D_{50s} and ρ_s is the sediment density. For a **bankfull** threshold of mobility, τ_{c50s} must equal the **bankfull** boundary shear stress. Thus combining (1) and (2) produces the simple **bankfull** threshold model enabling D_{50s} to be theoretically predicted from **bankfull** depth and slope

$$D_{50s} \approx 0.61hS/\tau^*_{c50s} \quad (3)$$

Here ρ and ρ_s are 1000 and 2650 kg/m^3 respectively and τ^*_{c50s} is a constant that will be evaluated later in the chapter.

Past investigations of the threshold channel concept have considered the entire channel, including the sidewalls, to be composed of loose **alluvium** at the threshold of motion and as such have discussed sidewall equations of motion (Lane, 1953; 1954, Lane and **Carlson**, 1953; Parker, 1978b). In this regard Parker (1978b) has commented on the apparent paradox of cross-section stability **in** threshold channels, in that beyond the threshold of motion active **bedload** transport occurs, yet the inherently more mobile sidewall grains remain stable. Parker (1978b) argues that outward turbulent momentum flux between the channel center and walls (i.e., sidewall effects) stabilizes sidewall grains that would otherwise tend to move down the bank toward the channel center. While sidewall effects will be accounted for in the current analysis, mobility of bank material as

conceptualized in past threshold channel studies is of little significance here, as most of the channels examined in the current study are forest streams with cohesive soil banks reinforced by shrub and tree roots.

The **bankfull** threshold model assumes that **all** channel roughness can be attributed to particle roughness, as indicated by the scaling of τ_{c50s} by D_{50s} in (2). While this is a common assumption for gravel-bedded rivers, it is usually an oversimplification. Other sorts of in-channel roughness are typically present, such as **bedforms** and large woody debris (**LWD**). Nevertheless, because (3) neglects these other roughness features, their effects can **be** investigated by **examination** of textural deviation from **the** simple model prediction. It is hypothesized that the presence of in-channel roughness elements other **than** grain roughness **will** cause increased momentum extraction resulting in reduced basal shear stress. Consequently, momentum extraction **will** be reflected **by surface** textures that are **finer** than the model prediction. **In** this analysis investigation of textural response to hydraulic roughness features will be limited primarily to effects caused by **bedform** and LWD roughness typical of forest channels. Wall effects will also be quantified, but roughness elements other than LWD and **bedforms** will only be given qualitative consideration.

Multiple scales of roughness are commonly accounted for through roughness or shear stress partitioning, which is predicated on the hypothesis that the total channel roughness and shear stress can be decomposed into linearly additive components each characterizing a particular roughness element (Einstein and **Barbarossa**, 1952; **Engelund**, 1966; Johnson, 1973; Smith and McLean, 1977; Hey, 1979; Parker and Peterson, **1980**; Prestegard, 1983; **Dietrich** et al., 1984 ; Hey, 1988; **Griffiths**, 1989; Nelson and Smith, 1989b; Wiberg and Smith, 1989; Petit, 1989; 1990; Robert, **1990**; Clifford et al., 1992; Yalin, 1992; Li, **1994**; Milar and Quick, 1994). The relevant shear stress partitioning equation for the current investigation is

$$\tau_0 = \tau_g + \tau_w + \tau_f + \tau_l \quad (4)$$

where the total **bankfull** boundary shear stress is partitioned into components expended on grains, τ_g , sidewalls, τ_w , bedforms, τ_f , and LWD, τ_l . Other components could also be included, representing shear stress dissipation caused by, for example, channel curvature, saltating grains, and live in-channel vegetation. The effective shear stress, τ' , is the shear **stress** that is available for sediment transport after correction for roughness features other than grain roughness, and is defined here as

$$\tau' = \tau_0 - \tau_w - \tau_f - \tau_l \quad (5)$$

In the case of a **bankfull** threshold channel, $\tau' = \tau_g$. **Bankfull** threshold channels that are only characterized by τ_g have a plane-bed morphology similar to the coarse-grained canals studied by Lane (1953; 1955) and Lane and **Carlson** (1953). As such, (3) predicts the median surface grain size of a wide, straight, **bankfull** threshold, plane-bed channel.

Sidewalls, **bedforms**, and LWD each dissipate channel shear stress in different ways. Sidewall effects are particularly influential in narrow channels ($W/h \leq 10$), causing turbulence due to momentum differences between the channel center and margins, effectively transferring a portion of the total boundary shear stress to the channel **walls** and reducing that over the channel bed (Parker, 1978b). The shear stress dissipated by channel walls additionally depends on the relative magnitude of bed and wall roughness length scales (**Shimizu**, 1989). **Bedforms** dissipate shear stress through simple form drag that is a function of **bedform** amplitude and wavelength (Smith and McLean, 1977; Nelson and Smith, 1989b). Woody debris roughness is a function of its amount, size, pitch, and orientation with respect to the flow. Mechanics of flow perturbation caused by LWD that

result in momentum extraction and consequent textural **fining** include: flow deceleration caused by woody debris skin roughness; form drag and turbulent energy dissipation around LWD obstructions; hydraulic jumps over woody debris steps; and general decline in water surface slope, and thus energy gradient, due to physical blockage of flow and back-water effects caused by LWD obstructions. It is hypothesized, through analogy with flow mechanics in meandering rivers (i.e., Furbish, 1991), that LWD roughness and its effects are locally intensive and progressively damped downstream away from a given obstruction.

In addition to hydraulic roughness features, the model prediction of grain **size** does not take into account effects of sediment supply. **Dietrich** et al. (1989) demonstrated that surface textures of laboratory plane-bed channels are responsive to sediment load (i.e., volume), fining when inundated with sediment, and coarsening when deprived. When deprived of sediment, small grains are selectively winnowed from exposed or low friction angle locations, ultimately resulting in an armored surface that is **coarser** and hydraulically rougher, compensating for any previous excess shear stress. In contrast, rough **bed-**surfaces that are inundated with sediment tend to trap smaller grains in sheltered or **high** friction angle locations, causing an overall surface fining and reduction in **bed** roughness that results in increased mobility of both material on and passing over the bed surface (see also Whiting et al., 1988); thus by decreasing surface roughness, textural lining allows increased sediment loads to be accommodated without significant bed aggradation (Dietrich et al., 1989).

Based on the findings of **Dietrich** et al. (1989), it is expected that within the threshold model framework textural **fining** in response to increased sediment loads will be expressed as a deviation from the predicted surface grain size. Furthermore, combining the **bankfull** threshold model with the dimensionless **bedload** transport rate, q^* , proposed by **Dietrich** et al. (1989) allows quantification of the degree of sediment loading. **Dietrich** et al.

(1989) defined q^* as **the bedload** transport rate of the surface material **normalized** by that of the load, where grain sizes of the load are approximated by the subsurface distribution (Milhous, 1973; Kuhnle, 1993)

$$q^* = \left(\frac{\tau_0 - \tau_{c50s}}{\tau_0 - \tau_{c50ss}} \right)^{1.5} = \left(\frac{\frac{\tau_0}{\tau_{c50ss}} - \frac{D_{50s}}{D_{50ss}}}{\frac{\tau_0}{\tau_{c50ss}} - 1} \right)^{1.5} \quad (6)$$

Commensurate with the discussion preceding (2), the q^* formulation assumes that general mobility of heterogeneous material can be approximated by mobility of the median grain size and so employs τ_{c50s} and τ_{c50ss} (Dietrich et al., 1989; Kinerson, 1990). The dimensionless **bedload** transport rate is essentially a sediment transport efficiency equation, ranging from 0 for armored, low sediment supply channels to 1 for unarmored channels **with** high sediment loading (Dietrich et al., 1989). A q^* of 0 indicates low sediment transport efficiency, while a q^* of 1 indicates maximum transporting efficiency.

The theoretical limits of textural response to changes in sediment supply can be determined by comparing the **bankfull** threshold model with (6). The threshold model assumes that τ_0 is equal to τ_{c50s} , which in terms of (6) corresponds to a q^* of 0. Thus, the **bankfull** threshold model represents armored conditions and the coarse limit of textural response described by q^* . The opposite extreme is a q^* of 1, which occurs when surface **fining** approaches the subsurface median grain size. Maximum transporting capacity and equilibrium conditions between bed surface and **bedload** occur at q^* values of 1. Under these later conditions, increases in **bedload** supply can only be accommodated by deposition. Consequently, D_{50ss} is the theoretical limit of sediment-induced textural fining. Examination of textural response within the grain size limits of D_{50s} and D_{50ss} provides a means to quantify the **degree** of sediment loading within a channel. Although developed

from studies of plane-bed channels, the q^* theory is applicable to other channel types provided that roughness effects are accounted for.

Threshold model predictions of median surface grain **size** and hypothesized textural responses to both **sediment** supply and in-channel roughness features are shown schematically in Figure 1.3. The **bankfull** threshold prediction of surface grain size corresponds to a plane-bed morphology with $q^*=0$ (i.e., low sediment supply and fully armored streambed). The subsurface median grain **size** is the limit of sediment-induced textural fining ($q^*=1$), but unfortunately cannot be predicted theoretically and must be determined by field investigation, as discussed further in the next chapter. Expression of these textural limits within the **bankfull** threshold model is simply another way to visualize the q^* theory. However, the threshold model has the further advantage of providing a means to assess textural response caused by hydraulic roughness elements.

DIMENSIONLESS CRITICAL SHEAR STRESS

Application of the threshold channel model and investigation of the preceding hypotheses requires choice of an appropriate dimensionless critical shear stress **value** for the median surface grain size, τ^*_{c50} , for use in (3). Shields (1936) demonstrated that τ^*_{c50} of near-uniform grains varies with critical boundary Reynolds Number, Re^*_c , from $1.8 \leq Re^*_c \leq 490$ and hypothesized based on analogy with Nikuradse's (1933) findings that τ^*_{c50} attains a constant **value** of about 0.06 beyond $Re^*_c \approx 490$ (Fig. 1.4). The critical boundary Reynolds Number is defined as $Re^*_c = u^*_c k_s / \nu$, where u^*_c is the critical shear velocity for incipient motion [$u^*_c = (\tau_c / \rho)^{0.5}$], k_s is the boundary roughness length scale, and ν is the kinematic viscosity. While Shields (1936) boundary Reynolds Numbers are not the same as Nikuradse's (1933), the general form of Shields' (1936) curve (Fig. 1.4) is quite similar to Nikuradse's (1933), indicating regions of hydraulically smooth,

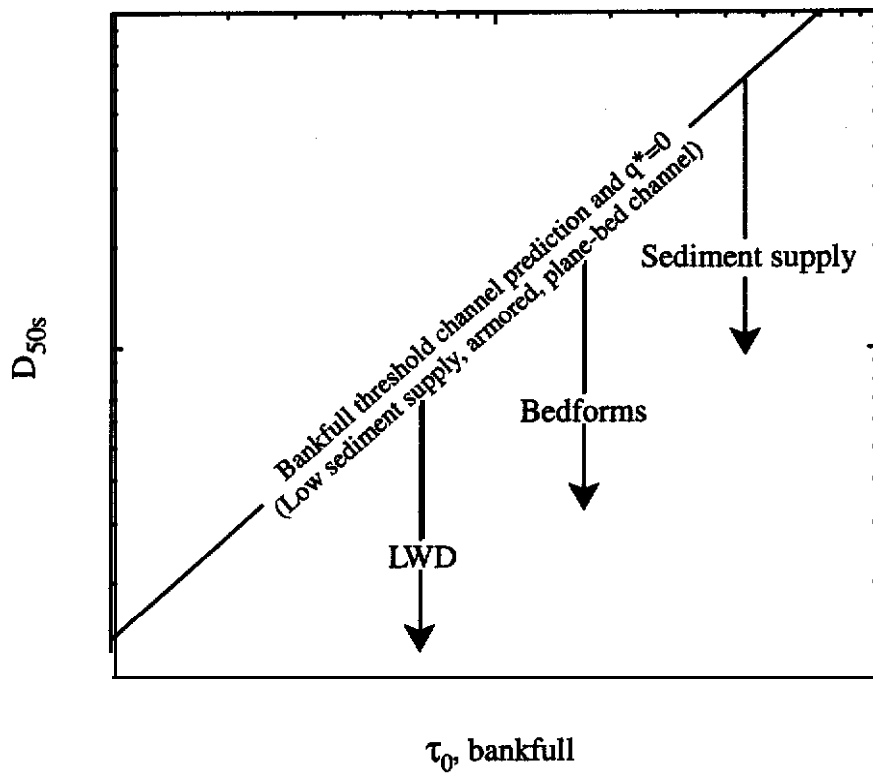


Figure 1.3 Schematic representation of the **bankfull** threshold model prediction of median surface grain size and hypothesized textural response to sediment supply and other hydraulic roughness elements.

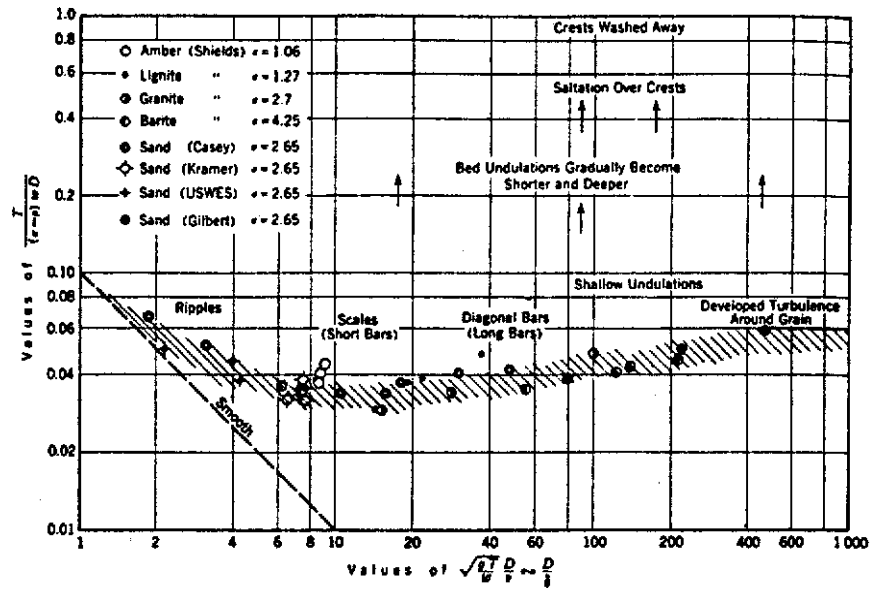


Figure 1.4 Shields' (1936) curve as presented by Rouse in Chang (1939).

transitional, and rough turbulent flow. Because **bedload** transport in most gravel-bedded streams is characterized by rough turbulent flow, the appropriate τ^*_{c50} value based on the Shields curve would be 0.06 for the current study. However, there have been numerous additions, revisions, and modifications of the Shields curve over the years, complicating the choice of τ^*_{c50}

Gessler (1971) recognized that the incipient motion of a particular grain **size** is inherently a statistical problem, depending on probability functions of both turbulent shear stress at the bed and intergranular geometry (i.e., friction angles) of the bed material, the later **being** controlled by grain shape, sorting, and packing (Miller and Byrne, 1966; Li and Komar, 1986; Kirchner et al., 1990, Buffington et al., 1992). Reanalyzing Shields (1936) data and correcting for sidewall effects and form drag, Gessler (1971) reports $\tau^*_{c50} \approx 0.046$ for a 50% probability of movement in rough turbulent flow. Without consideration of the probability of movement Miller et al. (1977) arrived at a similar rough turbulent-flow value, $\tau^*_{c50} \approx 0.045$, using compiled flume data from various sources. Miller et al. (1977) claim to have used “carefully selected data” to maximize the compatibility of their compiled data sources and avoid an otherwise **unmanageable** amount of scatter.” They only employed data that were derived from experiments using “flumes with parallel sidewalls where flows were uniform and steady over flattened beds of **unigranular**, rounded sediments”; sidewall corrections were applied and each source used a consistent **definition** of incipient motion. However, closer scrutiny of their compiled data shows that it is based on both uniform and non-uniform sediment mixtures, differing incipient motion definitions between studies, and in some cases **bedload** transport rates **influenced** by the presence of dune-ripple bedforms. Consequently, their data is much less controlled than a casual reading of their article would indicate.

Using a larger data set without any concern for differences in sediment characteristics, channel roughness, or definition of incipient motion, **Yalin** and Karahan

(1979, Fig. 5) also report $\tau^*_{c50} \approx 0.045$ for rough turbulent flow. They further demonstrate the existence of a second “Shields curve” for fully laminar flow, which for the same Re^*_c values behaves differently than the traditional Shields curve (derived from turbulent flow with variable hydrodynamic boundary roughness). The τ^*_{c50} values reported by Miller et al. (1977) and Yalin and Karahan (1979) are based on curves fit by eye through data sets with considerable scatter; in both studies τ^*_{c50} for rough turbulent flow has a range of about 0.02-0.065.

While the compilation studies of Miller et al. (1977) and Yalin and Karahan (1979) are fairly consistent with one another in their findings, they unfortunately combine data sets derived from quite different experimental conditions and methodologies without any assessment of compatibility. This casts some doubt on the veracity of such compilations. Continued proliferation of incipient motion studies using new definitions of initial motion further complicates comparison and understanding of published studies. Miller and others’ (1977) quote of Mark Twain is even more appropriate today: “Researchers have already cast much darkness on the subject, and if they continue their investigations we shall soon know nothing at all about it.”

In an attempt to make some sense of previous findings I have compiled all available τ^*_{c50} values, categorizing them on the basis of τ^*_{c50} type and incipient motion definition (Table 1.1). By τ^*_{c50} type I mean that τ^*_{c50} values have been variously reported for the median grain size of the surface, D_{50s} , subsurface, D_{50ss} , and laboratory sediment mixture, D_{50m} , the three of which are equal only for uniform grain sizes; corresponding dimensionless critical shear stress types are denoted here as τ^*_{c50s} , τ^*_{c50ss} , and τ^*_{c50m} . Expression of dimensionless critical shear stress in terms of the subsurface grain size distribution was popularized by Andrews (1982) who expressed the Shields stress of a given grain size of interest, $\tau^*_{c_i}$, as a power-law function of the ratio D_i/D_{50ss} ; Andrews (1982) found that for his data, D_i/D_{50ss} was better correlated with $\tau^*_{c_i}$ than was D_i/D_{50s} .

($r^2=0.98$ vs. 0.89). Unfortunately the Andrews (1982) expression introduced great confusion to the incipient motion literature in that some investigators subsequently used mobility thresholds of subsurface material in discussions of incipient motion of the bed *surface* (Parker et al., 1982; Parker and Klingeman, 1982; Komar, 1987a; Wilcock and Southard, 1988; Komar and Carling, 1991). It is well known that most gravel-bedded rivers are armored and that the surface and subsurface grain size distributions can be significantly different from one another (Milhous, 1973). It seems fundamentally intuitive then that any analysis of incipient motion of the bed surface should employ surface parameters (D_{50s} , τ^*_{c50s} , τ^*_{c50s} , etc.) rather than subsurface ones (D_{50ss} , τ^*_{c50ss} , τ^*_{c50ss} , etc.). Furthermore, poor recognition of the difference between τ^*_{c50ss} and τ^*_{c50s} by authors and subsequent users of data has in some instances led to erroneous applications. For example, using a power-law function for dimensionless critical shear stress, $\tau^*_{ci}=\alpha(D_i/D_{50})^\beta$, Komar (1987a) reported that $\alpha\approx 0.045$ for natural coarse-grained channels, but did not clearly specify that $D_{50}=D_{50ss}$ and thus $\alpha=\tau^*_{c50ss}$ (Appendix I, note 6); the corresponding unreported τ^*_{c50s} value is about 0.021-0.027 (Table 1.1). Mistakenly assuming that Komar (1987a) reported τ^*_{c50s} , Dietrich et al. (1989) erroneously used $\alpha=\tau^*_{c50ss}$ to calculate surface critical shear stresses from the Shields equation.

Each τ^*_{c50} type given in Table 1.1 is subdivided by the method used to measure incipient motion. The three most widely used methods are: 1) visual observation; 2) **bedload** sampling and extrapolation of transport rates to either a zero or low reference value; and 3) **bedload** sampling and development of competence functions. Visual observation is direct, but can be subjective depending on one's definition of how much movement constitutes "initial motion" (e.g., Kramer, 1935; USWES, 1935). Dimensionless critical shear stress values of the median surface grain size determined by extrapolation of transport rates depend on the particular reference value that is chosen

TABLE 1.1: Previously Reported τ^*_{c50} Values

SURFACE						
Source [£]	τ^*_{c50s}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50s} (mm)	Re^*_c [‡]	σ_g	Experimental Conditions
						<i>Reference Transport Rare</i>
Parker and Klingeman (1982) ¹	0.035 m	$\tau^*_{c_{ri}}=0.035(D_i/D_{50s})^{-0.78}$	5 4	10,001	0.75	Natural pool-riffle channel, with relatively subdued topography in the study reach. No form drag or sidewall correction. $D_{50s}/h_c \approx 0.15$ [¶] .
In Wilcock and Southard (1988) ² Milhous (1973)	0.027 m	$\tau^*_{c_{ri}}=0.073(D_i/D_{50ss})^{-0.98}$	5 4	8,784	0.75	Same as Parker and Klingeman (1982), but with $D_{50s}/h_c \approx 0.20$.
Ashworth and Ferguson (1989) ³	0.072 m	$\tau^*_{c_{ri}}=0.072(D_i/D_{50s})^{-0.65}$	-50	-11,660		Natural pool-riffle channel, variable sinuosity. Sidewall effects accounted for. $D_{50s}/h_c \approx 0.11$.
	0.054 m	$\tau^*_{c_{ri}}=0.054(D_i/D_{50s})^{-0.67}$	-57.5	-12,694		Natural pool-riffle channel, mildly braided. Sidewall effects accounted for. $D_{50s}/h_c \approx 0.10$.
	0.087 m	$\tau^*_{c_{ri}}=0.087(D_i/D_{50s})^{-0.92}$	-69	-24,207		Natural braided channel. $D_{50s}/h_c \approx 0.13$. Sidewall effects accounted for.
Parker (1990) ⁴	0 . 0 3 3 m	$\tau^*_{c_{ri}}=0.039(D_i/D_{gs})^{-0.90}$	5 5	9,982	1.02	Same as Parker and Klingeman (1982). but with $D_{50s}/h_c \approx 0.16$.
<i>Largest Mobile Grain</i>						
Andrews and Erman (1986) ⁵	0.047 m	$\bar{\tau}^*_{c_{qi}}=0.083(D_i/D_{50ss})^{-0.87}$	58	12,200	0.97	Natural, meandering, pool-rifle channel. No form drag or sidewall correction. $D_{50s}/h_c \approx 0.15$.

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[£] **Italicised numbers are** keyed to Appendix I notes.

[†] See p. 144 for notation not previously defined in text.

u=uniform grain sizes ($\sigma_g \leq 0.5\phi$), **m**=mixed grain sizes ($\sigma_g > 0.5\phi$), where σ_g is the graphic standard deviation defined as $(\phi_{84}-\phi_{16})/2$ (Folk, 1974).

[‡] $Re^*_c = u^*_{c50} D_{50} / \nu$. Most values calculated by JMB based on reported data. For example using $\tau^*_{c_{r50}}$ and D_{50s} reported by Parker and Klingeman (1982) I calculated $\tau_{c_{r50}} = \tau^*_{c_{r50}} D_{50s} (\rho_s - \rho) g$ and $u^*_c = (\tau_{c_{r50}} / \rho)^{0.5}$, allowing determination of $Re^*_c = u^*_c D_{50s} / \nu$. Where not reported, it was assumed that ρ_s and ρ were 2650 and 1000 kg/m³, respectively, and that $\nu = 10^{-6}$ m²/s.

[¶] Most h_c values back-calculated from depth-slope products using data reported by authors or calculated by JMB.

TABLE 1.1 cont.

Source [£]	τ^*_{c50s}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50s} (mm)	Re^*_c [‡]	σ_{gs}	Experimental Conditions
In Komar (1987a)⁶						
Milhous (1973) ⁷	0.027 m	$\tau^*_{cqi}=0.044(D_i/D_{50ss})^{-0.43}$	60	10,288	0.71	Same as Parker and Klingeman (1982). but with $D_{50s}/h_c=0.20$.
Carling (1983) ⁸	0.022 m	$\tau^*_{cqi}=0.045(D_i/D_{50ss})^{-0.68}$	62	9,378		Natural, steep, gravel-bedded channel. No form drag or sidewall correction. $D_{50s}/h_c=0.27$.
Hammond et al. (1984) ⁹	0.022 m	$\tau^*_{cqi}=0.045(D_i/D_{50ss})^{-0.71}$	21	1,816	0.56	Natural tidal channel. Plane-bed.
In Komar (1987b)						
Fahnestock (1963) ¹⁰	0.029 m		128	31,375	1.50	Natural, proglacial, braided channel. No form drag or sidewall correction.
In Komar and Carling (1991)¹¹						
Milhous (1973)	0.029 m	$\tau^*_{cqi}=0.059(D_i/D_{50ss})^{-0.64}$	60	10,662	0.71	Same as Parker and Klingeman (1982). but with $D_{50s}/h_c=0.19$.
Komar and Carling (1991)	0.039 m	$\tau^*_{cqi}=0.039(D_i/D_{50s})^{-0.82}$	62	12,487		Same as Carling (1983) in Komar (1987a), but with $D_{50s}/h_c=0.15$.
Milhous (1973) ¹²	0.025 m		60	9,900	0.71	Same as Parker and Klingeman (1982), but with $D_{50s}/h_c=0.22$.
Carling (1983) ¹³	0.030 m	$\tau^*_{cqi}=1.17Re^*_i^{-0.46}$	62	10,952		Natural, steep, gravel-bedded channel (Great Eggeshope Beck). No form drag or sidewall correction. $D_{50s}/h_c=0.19$.
	0.111 m	$\tau^*_{cqi}=4.99Re^*_i^{-0.42}$	87	32,356		Natural, steep, gravel-bedded channel (Carl Beck). No form drag or sidewall correction. $D_{50s}/h_c=0.24$.
Ferguson (1994) ¹⁴	0.074 m		106	37,770	1.06	Natural boulder-bed stream. Bedform type not reported. Form drag and sidewall correction not explicitly considered. $D_{50s}/h_c=0.3$ 1.
	0.078 m		104	37,685	1.01	Same as above, but with $D_{50s}/h_c=0.28$.
	0.061 m		109			Same as above, but with $D_{50s}/h_c=0.33$.
	0.070 m		96	35,759,31,662	1.111,22	Same as above, but with $D_{50s}/h_c=0.42$.
	0.047 m		75	17,915		Natural channel. Bedform type not reported. Form drag and sidewall corrections not explicitly considered.
----- <i>Other</i>						
Kalinske (1947) ¹⁵	0.039 u					

TABLE 1.1 cont.

Source [‡]	τ^*_{c50s}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50s} (mm)	$Re^*_{c\ddagger}$	σ_{gs}	Experimental Conditions
Çeçen and Bayazit (1973) ¹⁶	0.044 m ⁴⁸		14.6	1,481	0.72	Straight, rectangular flume. Plane-bed. No sidewall correction. $D_{50s}/h_c=0.26$.
Kirchner et al. (1990) ¹⁷	-0.100 m		3.74-4.85	291-430	-0.94-1.18	Straight, rectangular flume. Plane-bed (?).
		$\tau^*_{ci} = \left(\frac{1}{\tan \Phi_i} \frac{3C_D}{\pi \kappa^2} \int_{p_i^* - e_i^*}^{p_i^*} \sqrt{1 - (2z^* - (2p_i^* - 1))^2} [\ln(z^* D_i^* + 1)]^2 dz^* + \frac{3C_L}{4\kappa^2} \left\{ [\ln(p_i^* D_i^* + 1)]^2 - [\ln(p_i^* D_i^* - D_i^* + 1)]^2 \right\} \right)^{-1}$				
Buffington et al. (1992) ¹⁸	-0.100 ~u, m	"	4.1-45	334-12,145	0.67-1.50	Natural, pool-riffle channel.
Jiang and Haff (1993) ¹⁹	0.086-0.161 m		7.2 (?)	700-1000		Simulated heterogeneous bed surface undergoing a "slab" shear.

MIXTURE

Source	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	$Re^{*\ddagger}$	σ_{gm}	Experimental Conditions
						<i>Reference Transport Rate</i>
In Shields (1936) ²⁰ Shields (1936)	0.036 ~u		0.36	-6.3	0.30	Straight, rectangular flume. Various bedform types. Sidewall correction, but no form drag correction. Grains composed of barite.
	0.034 ~u		1.52	52	0.35	"
	0.043 ~u		2.76	127	0.41	"
	0.045 ~u		3.44	205	0.16	"
	0.039 ~u		2.46	115	0.22	"
	OMI ~u		0.69	15	0.33	"
	-0.037 m		1.56	-8.7	0.59	Same as above, but with amber grains.
	-0.041 m		1.56	-8.9	0.59	"
	-0.044 m		1.56	-9.3	0.59	"
	-0.029 ~u		0.85	-15	0.23	Same as above, but with granitic (natural) grains.
	-0.034 ~u		1.23	-29	0.23	"

TABLE 1.1 cont.

Source [£]	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	Re^*_c [‡]	σ_{gm}	Experimental Conditions
	0.054 ~u	"	"	511	"	Same as above, but with $D_{50m}/h_c=0.12$.
	0.050 ~u	"	12.0	1,174	<0.21	Same as above, but with $D_{50m}/h_c=0.33$.
	0.047 ~u	"	"	1,135	"	Same as above, but with $D_{50m}/h_c=0.59$.
	0.054 ~u	"	"	1,203	"	Same as above, but with $D_{50m}/h_c=0.83$.
	0.059 ~u	"	"	1,239	"	Same as above, but with $D_{50m}/h_c=1.00$.
	0.067 ~u	"	"	1,302	"	Same as above, but with $D_{50m}/h_c=1.04$.
	0.083 ~u	"	"	1,425	"	Same as above, but with $D_{50m}/h_c=0.63$.
	0.056 ~u	"	22.5	3,015	<0.08	Same as above, but with $D_{50m}/h_c=0.90$.
	0.056 ~u	"	"	2,969	"	Same as above, but with $D_{50m}/h_c=1.05$.
	0.061 ~u	"	"	3,052	"	Same as above, but with $D_{50m}/h_c=1.47$.
	0.072 ~u	"	"	3,268	"	Same as above, but with $D_{50m}/h_c=1.73$.
	0.081 ~u	"	"	3,376	"	
	0.099 ~u	"	"	3,593	"	
Misri et al. (1984) ²⁷	-0.023 m		6.02	-285	1.65	Straight, rectangular flume. Bedform type not reported. Sidewall effects and (?) form drag corrected.
In Bridge and Dominic (1984) ²⁸ upper stage plane-bed: Gilbert (1914)	0.040 ~u		0.30	4.2		straight, rectangular flume. Upper stage plane-bed. Sidewall correction. ²⁸
	0.052 ~u		0.38	6.9		"
	0.042 ~u		0.51	9.6		"
	0.030 ~u		0.79	16		"
Guy et al. (1966) ²⁹	0.040 ~u		0.19	2.1	0.45	"
	0.040 m		0.28	3.3	0.81	"
	0.040 m		0.32	4.6	0.65	"
Williams (1970) ³⁰ Lower stage plane-bed: Gilbert (1914)	0.040 ~u		1.35	40	0.20	straight, rectangular flume. Lower stage plane-bed. Sidewall correction. ²⁸
	0.041 ~u		4.94	286		"
Williams (1970) ³⁰ Fernandez Luque and van Beek (1976) ³¹	0.040 ~u		1.35	40	0.20	"
	0.040 ~u		0.9-3.3	22-152	<0.49	"
In Bathurst et al. (1987) ³² BFFL (Ecole Polytechnique Fédérale de Lausanne)	0.052 ~u?		11.5	-900		Straight, rectangular flume. Various bedforms. Sidewall correction, but no form drag correction. $D_{50m}/h_c=0.08$.
	0.063 ~u?	$\tau^*_{c150m} = \tau_{c150m} / [(\rho_s - \rho)gD_{50m}(\tan\Phi \cos\theta - \sin\theta)]$	"	-951		Same as above, but with $D_{50m}/h_c=0.10$.

TABLE 1.1 cont.

Source [£]	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D _{50m} (mm)	Re* _c [‡]	σ_{gm}	Experimental Conditions
Bathurst et al. (1979) ^{''}	0.070 ~u?	"	"	-1.069		Same as above. but with D _{50m} /h _c =0.12.
	0.062 ~u	"	22.2	-3.162	0.34	Same as above, but with D _{50m} /h _c =0.12.
	0.087 ~u	"	"	-3.381	"	Same as above, but with D _{50m} /h _c =0.27.
	0.102 ~u	"	"	-3.614	"	Same as above, but with D _{50m} /h _c =0.39.
	0.113 ~u	"	"	-3.799	"	Same as above, but with D _{50m} /h _c =0.50.
	0.115 ~u	"	"	-3.929	"	Same as above, but with D _{50m} /h _c =0.65.
	0.061 ~u?	"	44.3	-8.050		Same as above, but with D _{50m} /h _c =0.35.
	0.068 ~u?	"	"	-8.463		Same as above, but with D _{50m} /h _c =0.53.
	0.087 ~u?	"	"	-8.750		Same as above, but with D _{50m} /h _c =0.59.
	0.088 ~u?	"	"	-9.354		Same as above, but with D _{50m} /h _c =0.79.
	-0.094 ~u?	"	8.8	-8.075		Flume. Bedform types not reported by Bathurst et al. (1987). Sidewall correction?
	-0.126 ~u?	"	"	-1.000		D _{50m} /h _c =0.14.
-0.182 ~u?	"	"	-1.160		Same as above, but with D _{50m} /h _c =0.27.	
-0.097 ~u?	"	34	-6.310		Same as above, but with D _{50m} /h _c =0.31.	
						Same as above, but with D _{50m} /h _c =0.57.
In Day (1980b) ³⁴						
USWES (1935)	-0.050 m		0.42	7.7	0.86	Flume. Bedform type not reported. No form drag or sidewall correction.
	-0.047 m		0.44	8.1	0.59	"
	-0.034 m		4.10	195	0.54	"
Day (1980a)	-0.024 m		1.75	46	2.10	"
	-0.029 m		1.55	42	1.70	"
In Wilcock and Southard (1988) ³⁵						
Day (1980a)	0.037 m	$\tau^*_{c_{ri}}=0.037(D_i/D_{50m})^{-0.81}$	1.82	60	2.10	Flume. Bedform type not reported. No form drag or sidewall correction (?).
	0.037 m	$\tau^*_{c_{ri}}=0.037(D_i/D_{50m})^{-0.95}$	1.57	48	1.70	"
Dhamotharan et al. (1980)	0.071 m	$\tau^*_{c_{ri}}=0.071(D_i/D_{50m})^{-1.1}$	2.16	108	1.43	Flume. Bedform type not reported. No form drag or sidewall correction (?).
Misri et al. (1984)	0.048 m	$\tau^*_{c_{ri}}=0.048(D_i/D_{50m})^{-1.0}$	2.36	101	1.05	Straight, rectangular flume. Bedform type not reported. Sidewall and (?) form drag correction.
	0.042 m	$\tau^*_{c_{ri}}=0.042(D_i/D_{50m})^{-0.95}$	3.81	194	1.65	"
	0.037 m	$\tau^*_{c_{ri}}=0.037(D_i/D_{50m})^{-0.92}$	4.00	196	1.29	"

TABLE 1.1 cont.

Source [‡]	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	Re^*_c [‡]	σ_{gm}	Experimental Conditions
Wilcock (1987) ³⁶	0.030 m	$\tau^*_{cH}=0.030(D_i/D_{50m})^{-1.0}$	1.83	61	0.53	Straight, rectangular flume. Various bedforms. Sidewall and form drag correction applied.
	0.036 m	$\tau^*_{cH}=0.036(D_i/D_{50m})^{-0.97}$	1.83	67	1.06	
	0.023 -u	$\tau^*_{cH}=0.023(D_i/D_{50m})^{-0.98}$	0.67	12	0.29	"
	0.037 -u	$\tau^*_{cH}=0.037(D_i/D_{50m})^{-1.1}$	5.28	332	0.20	Straight, rectangular flume. Plane-beds. Sidewall correction applied.
----- <i>Visual Observation</i> -----						
Kramer (1935) ³⁷	0.048 m		0.52	8.5	0.81	Straight, rectangular flume. Plane-bed. No sidewall correction.
	0.055 m		"	9.4	"	"
	0.045 m		"	8.4	"	"
	0.047 m		"	8.5	"	"
	0.040 m		0.51	7.6	0.74	"
	0.042 m		"	7.6	"	"
	0.039 m		"	7.5	"	"
	0.034 m		"	6.9	"	"
	0.038 m		0.56	8.3	0.62	"
	0.043 m		"	8.8	"	"
	0.042 m		"	8.6	"	"
	0.041 m		"	8.7	"	"
	Meyer-Peter and Müller (1948) ³⁸	0.033~u?		3.2	127	
		$\tau^*_{c50m}=[\tau_{c50m}(Q_s/Q)(n_g/n_0)^{3/2}]/[(\rho_s-\rho)gD_{50m}]$				
0.032 ~u?			2.7	98		"
0.037 ~u?			3.8	183		"
0.030 ~u?			3.6	157		"
0.039 ~u?			3.66	174		"
0.040 ~u?			3.66	190		"
0.037 ~u?			8.5	676		"
0.050 ~u?			7.4	603		"
0.047 ~u?			8.5	762		"
0.040 ~u?			3.14	152		"
0.033~u?			1.86	57		Same as above, but with angular grains.
0.025 ~u?			3.14	107		"
0.033 ~u?			3.1	127		"

TABLE 1.1 cont.

Source [£]	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	Re^*_c [‡]	σ_{gm}	Experimental Conditions
White (1940) ³⁹	0.043 ~u?		3.14	165		"
	0.038 ~u?		3.66	179		"
	0.040 ~u?		3.06	144		"
	0.040 ~u?		2.58	112		"
	0.048 ~u?		2.61	124		"
	0.050 ~u?		4.04	233		"
	0.043 ~u?		4.34	273		"
	0.043 ~u?		2.190			"
	0.338 ~u		0.21	0.04		Straight, rectangular flume. Plane-bed. No sidewall correction. Fluid medium of lubricating oil. Entirely laminar flow.
	0.168 ~u		0.90	0.30		
0.180 ~u		0.122	2.4		Constant-drag nozzle. Plane-bed (?). No sidewall correction. Water fluid medium. Entirely laminar flow.	
0.119 ~u		0.90	33		Constant-drag nozzle. Plane-bed (?). No sidewall correction. Fully (?) turbulent flow.	
0.101 ~u		5.6	480		"	
0.064 ~u		0.71	35		Constant-drag nozzle. Plane-bed (?). No sidewall correction. Steel shot grains. Fully (?) turbulent flow.	
0.098 ~u		0.90	80		Constant-drag nozzle. Plane-bed (?). No sidewall correction. Fluid medium of air. Fully (?) turbulent flow.	
Neill (1967)	0.102 ~u		5.6	1,280		"
	0.024 ~u?		6.2	297		Straight, rectangular flume. Plane-bed. No sidewall correction. $D_{50m}/h_c=0.12$.
	0.033 ~u?		"	347		Same as above, but with $D_{50m}/h_c=0.11$.
	0.038 ~u?		"	372		Same as above, but with $D_{50m}/h_c=0.07$.
	0.034 ~u?		"	351		Same as above, but with $D_{50m}/h_c=0.07$.
	0.042 ~u?		"	388		Same as above, but with $D_{50m}/h_c=0.06$.
	0.045 ~u?		"	404		Same as above, but with $D_{50m}/h_c=0.05$.
	0.034 ~u?		"	348		Same as above, but with $D_{50m}/h_c=0.05$.
	0.037 ~u?		"	364		Same as above, but with $D_{50m}/h_c=0.04$.
	0.035 ~u?		"	353		Same as above, but with $D_{50m}/h_c=0.04$.
	0.040 ~u?		8.5	606		Same as above, but with $D_{50m}/h_c=0.28$.
	0.040 ~u?		"	602		Same as above, but with $D_{50m}/h_c=0.14$.
	0.062 ~u?		"	753		Same as above, but with $D_{50m}/h_c=0.07$.
	0.058 ~u?		"	729		Same as above, but with $D_{50m}/h_c=0.05$.
	0.033 ~u?		20.0	1,969		Same as above, but with $D_{50m}/h_c=0.55$.
0.034 ~u?		"	2,001		Same as above, but with $D_{50m}/h_c=0.39$.	

TABLE 1.1 cont.

Source ^f	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	Re^*_c [‡]	σ_{gm}	Experimental Conditions
white (1970)	0.029 ~u?	"	"	1,856		Same as above, but with $D_{50m}/h_c=0.33$.
	0.034 ~u?	"	"	2,007		Same as above, but with $D_{50m}/h_c=0.23$.
	0.040 ~u?	"	"	2,178		Same as above, but with $D_{50m}/h_c=0.18$.
	0.036 ~u?	"	"	2,073		Same as above, but with $D_{50m}/h_c=0.14$.
	0.043 ~u?	"	"	2,263		Same as above, but with $D_{50m}/h_c=0.11$.
	0.028 ~u?	"	5.0	228		Straight, rectangular flume. Plane-bed. No sidewall correction. Glass ball sediment. $D_{50m}/h_c=0.08$.
	0.042 ~u?	"	"	279		Same as above, but with $D_{50m}/h_c=0.04$.
	0.048 ~u?	"	"	295		Same as above, but with $D_{50m}/h_c=0.04$.
	0.044 ~u?	"	"	284		Same as above, but with $D_{50m}/h_c=0.04$.
	0.043 ~u?	"	"	280		Same as above, but with $D_{50m}/h_c=0.03$.
	0.053 ~u	"	2.2	-38		straight, rectangular flume. Plane-bed. Sidewall correction. Polystyrene grains.
	0.037 ~u	"	2	-53		Same as above, but with PVC grains.
	0.055 ~u	"	0.17	2.1		Same as above, but with natural grains.
	0.058 ~u	"	0.153	1.8		"
	0.071 ~u	"	0.133	1.6		"
	0.066 ~u	"	0.093	0.93		"
	0.073 ~u	"	0.077	0.73		"
	0.125 ~u	"	0.044	0.42		"
	0.112 ~u	"	0.033	0.26		"
	0.102 ~u	"	0.030	0.21		"
	0.103 ~u	"	0.029	0.20		"
	0.146 ~u	"	0.028	0.23		"
	0.110 ~u	"	0.024	0.16		"
	0.151 ~u	"	0.016	0.10		"
	0.037 ~u	"	2.2	-15		Straight, rectangular flume. Plane-bed. Sidewall correction. Polystyrene grains in Mentor 28 oil. Fully laminar flow (?).
	0.034 ~u	"	2	-40		Same as above, but with PVC grains.
	0.132 ~u	"	0.133	0.28		Same as above, but with natural grains
0.122 ~u	"	0.093	0.16		"	
0.166 ~u	"	0.077	0.14		"	
0.218 ~u	"	0.046	0.07		"	
0.254 ~u	"	0.033	0.05		"	
0.288 ~u	"	0.030	0.04		"	
0.219 ~u	"	0.025	0.03		"	
Grass (1970)"	0.141 (0.174) ~u	"	0.090	0.88 (0.97)		straight, rectangular flume. Plane-bed. Sidewall effects accounted for.
	0.131 (0.154) ~u	"	0.090	0.84 (0.91)		"

TABLE 1.1 cont.

Source ^f	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D _{50m} (mm)	Re [*] _{c[‡]}	σ_{gm}	Experimental Conditions	
Everts (1973) ⁴¹	0.110 (0.131)	~u	0.115	1.6 (1.7)		"	
	0.086 (0.095)	~u	0.138	1.8 (1.9)		"	
	0.069 (0.093)	~u	0.165	2.1 (2.5)		"	
	0.072 (0.079)	~u	0.195	2.8 (2.9)		"	
	0.058 (0.091)	m	0.143	1.6 (2.0)		"	
	0.023	~u		3.57	145		Straight, rectangular flume. Plane-bed. Sidewall correction applied.
	0.027	~u			157		"
	0.029	~u		"	162		"
	0.023	~u		1.79	51		"
	0.025	~u		"	54		"
	0.019	~u		"	47		"
	0.017	~u		"	44		"
	0.017	~u		0.895	16		"
	0.021	~u		"	17		"
	0.018	~u			16		"
	0.020	~u			17		"
	0.020	~u		0.508	7.2		"
	0.024	~u		"	8.0		"
	0.022	~u		"	7.7		"
	0.025	~u		"	8.1		"
	0.029	~u		0.359	5.2		"
	0.026	~u		"	4.9		"
	0.027	~u		"	5.1		"
	0.023	~u		"	4.6		"
	0.032	~u		0.254	3.3		"
	0.035	~u		"	3.4		"
	0.041	~u		"	3.7		"
	0.039	~u		0.18	2.1		"
	0.046	~u		"	2.3		"
	0.052	~u		0.127	1.5		"
	0.052	~u		"	1.5		"
	0.040	~u		"	1.3		"
0.056	~u		0.18	3.9		Same as above, but with ilmenite grains	
0.056	~u		"	3.9		"	
0.062	~u		"	4.1		"	
0.058	~u		0.127	2.3		"	
0.060	~u		"	2.4		"	
0.059	~u		"	2.4		"	
0.063	~u		"	2.4		"	
0.057	~u		0.09	1.4		"	

TABLE 1.1 cont.

Source ^f	τ^*_{c50m}	Proposed τ^*_c Function Other than the Shields Equation [†]	D_{50m} (mm)	Re^*_c [‡]	σ_{gm}	Experimental Conditions
Fernandez Luque and van Beek (1976) ⁴²	0.070 ~u		"	1.4		"
	0.058 ~u		"	1.6		"
	0.081 ~u		"			"
	-0.038 ~u		0.9	~18	<0.49	straight, rectangular flume. Plane-bed. Sidewall effects accounted for.
	-0.037 ~u		1.8	-51	"	"
	-0.047 ~u		3.3	-127	"	"
Yalin and Karahan (1979) ⁴³	-0.043 ~u		1.8	-74	"	Same as above, but with magnetite grains.
	-0.038 ~u		1.5	-16	"	Same as above, but with walnut (shell?) grains.
	0.038 ~u, m?		1.00	25	-0.34- 0.54	Straight, rectangular flume. Plane-bed. Sidewall effects corrected.
	0.030 ~u, m?		0.56	9.4	"	"
	0.113 ~u, m?		0.10	1.5	"	"
	0.036 ~u, m?		0.40	6.1	"	"
	0.053 ~u, m?		0.19	2.5	"	"
	0.079 u		0.14	1.8	"	Same as above, but with glass bead grains.
	0.178 ~u, m?		1.00	0.13	"	Straight, rectangular flume. Plane-bed. Sidewall effects corrected. Natural grains in water-glycerin mixture. Laminar flow.
	0.156 ~u, m?		1.88	0.30	"	"
	0.135 ~u, m?		2.86	0.55	"	"
	0.172 ~u, m?		0.56	0.05	"	"
	0.110 ~u, m?		1.00	0.78	"	"
0.092 ~u, m?		1.88	1.9	"	"	
0.141 ~u, m?		0.56	0.38	"	"	
0.086 ~u, m?		2.86	3.4	"	"	
0.091 ~u, m?		2.86	3.5	"	"	
0.134 ~u, m?		1.00	0.86	"	"	
0.143 ~u, m?		0.56	0.38	"	"	
0.110 ~u, in?		1.88	2.0	"	"	
0.140 ~u, m?		0.56	0.80	"	"	
0.069 ~u, m?		2.86	6.4	"	"	
0.086 ~u, m?		1.88	3.8	"	"	
0.106 ~u, m?		1.00	1.6	"	"	

TAB E 1.1 cont

Source	τ_{c50ss}	Proposed τ_c Function Other than the Shields Equation†	D_{50ss} (mm)	Re^{*+}	σ_{gs}	Experimental Conditions
Parker and Klingeman (1982) ⁴⁴ In Wilcock and Southard (1988)	0.088 m	$\tau_{c_{ri}}^* = 0.088(D_i/D_{50ss})^{-0.98}$	20	3,574	2.27	Same as Parker and Klingeman (1982).
Milhous (1973)	0.073 m	$\tau_{c_{ri}}^* = 0.073(D_i/D_{50ss})^{-0.98}$	19.5	3,134	2.27	Same as Parker and Klingeman (1982).
<i>Largest Mobile Grain</i>						
Andrews (1982) In Komar (1987a) ⁴⁵	0.083 m	$\tau_{c_{qi}}^* = 0.083(D_i/D_{50ss})^{-0.87}$				
Milhous (1973)	0.044 m	$\tau_{c_{qi}}^* = 0.044(D_i/D_{50})^{-0.43}$	20	2,528	2.67	Same as Parker and Klingeman (1982).
Carling (1983)	0.045 m	"	20	2,457		Same as in Komar (1987a).
Hammond et al. (1984) In Komar and Carling (1991)	0.045 m	$\tau_{c_{qi}}^* = 0.045(D_i/D_{50ss})^{-0.71}$	7.5	554		"
Milhous (1973)	0.059 m	$\tau_{c_{qi}}^* = 0.059(D_i/D_{50ss})^{-0.64}$	20	2,927	2.67	Same as Parker and Klingeman (1982).

£ Italicised numbers are keyed to Appendix I notes.

† See p. 144 for notation not previously defined in text.

u=uniform grain sizes ($\sigma_g \leq 0.5\phi$), m=mixed grain sizes ($\sigma_g > 0.5\phi$), where σ_g is the graphic standard deviation defined as $(\phi_{84}-\phi_{16})/2$ (Folk, 1974).

‡ $Re_c^* = u_c^* D_{50} / \nu$. Most values calculated by JMB based on reported data. For example using $\tau_{c_{150}}^*$ and D_{50s} reported by Parker and Klingeman (1982) I calculated $\tau_{c_{150}}^* = \tau_{c_{150}}^* D_{50s} (\rho_s - \rho) g$ and $u_c^* = (\tau_{c_{150}}^* / \rho)^{0.5}$, allowing determination of $Re_c^* = u_c^* D_{50s} / \nu$. Where not reported, it was assumed that ρ_s and ρ were 2650 and 1000 kg/m³, respectively, and that $\nu = 10^{-6}$ m²/s.

¥ Most h_c values back-calculated from depth-slope products using data reported by authors or calculated by JMB.

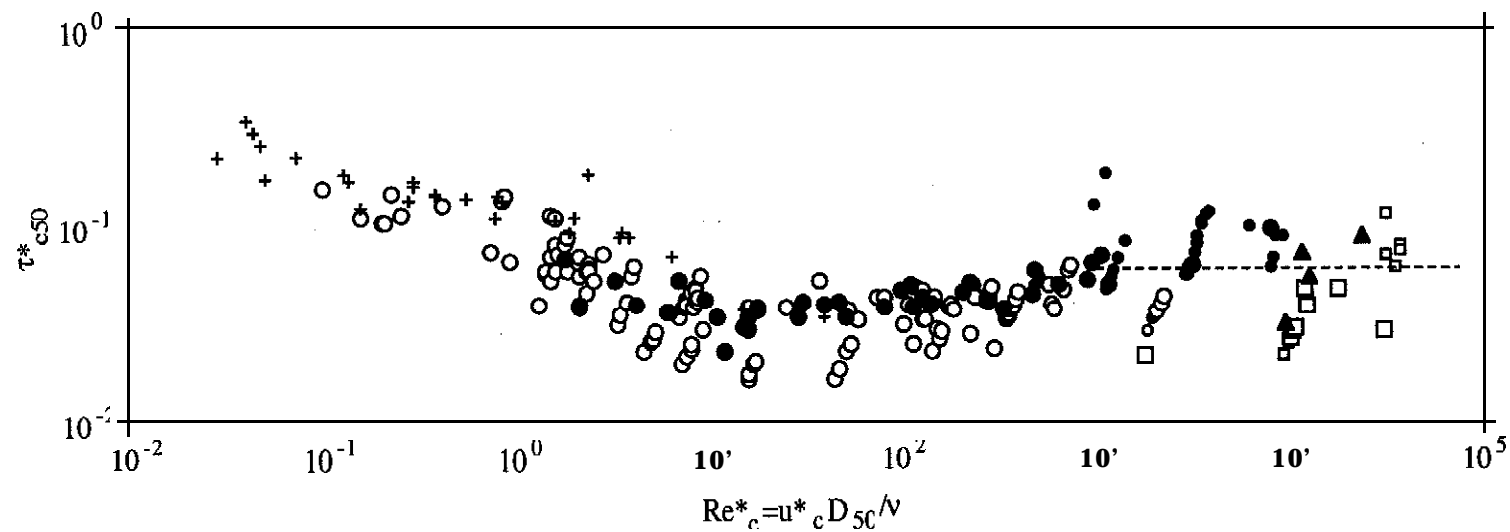
(Paintal, 1971; Misri et al., 1984; **Wilcock**, 1988). Competence functions are based on relations between shear stress and the largest mobile grain size, from which one can establish the critical dimensional and dimensionless shear stresses for a given size of interest. Competence functions are, however, sensitive to the sampling device used, technique, and availability of coarse grain sizes (**Wilcock**, 1992). In this analysis τ^*_{c50} values **corresponding** to these three methods of measuring incipient motion are respectively symbolized as τ^*_{cv50} , τ^*_{cr50} , and τ^*_{cq50}

Where data were available Table 1.1 also reports D_{50} , Re^*_c , and σ_g values, as well as experimental conditions and proposed τ^*_{ci} expressions other than Shields (1936). In many cases Re^*_c values were not reported by a given source, but could be calculated from other presented data; to be consistent with Shields (1936) I took $k_s=D_{50}$, however, as will be discussed later it is recommended that this common practice be **re-examined**, particularly for data from natural, heterogeneous, gravel-bedded streams. The sorting coefficient, σ_g , is Folks (1974) graphic standard deviation defined as $(\phi_{84}-\phi_{16})/2$, where ϕ_{84} and ϕ_{16} are the 84th and 16th percentiles of the grain size distribution expressed in units of the phi (\log_2) scale. In many cases τ^*_{c50} values (or **particular** types of τ^*_{c50}) were not explicitly reported by a source, but could be calculated from the equations and data presented by the author(s); detailed notes are given in Appendix I, keyed to italicized numerals in Table 1.1. Dimensionless critical shear stress values for subsurface median grain sizes (τ^*_{c50ss}) are presented in Table 1.1 for comparison with other τ^*_{c50} types, but will not be considered in this analysis as the concern here is choosing an appropriate τ^*_{c50} value for surface mobility.

By analogy with Folks (1974) sorting definitions, near-uniform sediments (i.e., well-sorted) are defined here as those with $\sigma_g \leq 0.5$, while mixed-grain sediments **are** those with $\sigma_g > 0.5$. With this definition it can be seen that some of the laboratory sediment mixtures used by Shields (1936) are mixed-grain, contrary to popular belief (Table 1.1).

Sorting is of significance because of its **influence** on friction angles and hence critical dimensional and dimensionless shear stresses (**Buffington** et al., 1992). Poorer sorted sediments tend to have lower friction angles and correspondingly lower τ_{ci} and τ_{ci}^* values. Sorting is of further significance for establishing the reliability of mixture incipient motion as a measure of surface mobility (i.e., establishing that $\tau_{c50m}^* \approx \tau_{c50s}^*$). All experiments reporting dimensionless critical shear stress in terms of the sediment mixture (τ_{c50m}^*) were conducted in flumes. Of these the reference-based values (τ_{cr50m}^*) were determined from **bedload** transport data commonly collected after attainment of **equilibrium** conditions of slope, **bedform** character, and transport rate. As such, the actual surface grain **size** distribution of initially poorly sorted mixtures may not resemble, at the time of measurement, the initial mixture distribution due to potential **textural** responses to relative conditions of sediment supply and transport capacity. **Dietrich** et al. (1989) have shown that heterogeneous bed surfaces coarsen when deprived of sediment and fine when inundated, reflecting the magnitude of sediment supply relative to transport capacity. Because of this potential textural response, τ_{cr50m}^* values **from** mixed-grain experiments will not be considered here as they may not accurately represent the threshold of surface mobility; depending on the direction of textural response, τ_{cr50m}^* values could over- or underestimate actual dimensionless critical shear stress **values** of the surface (τ_{cr50s}^*). D_{50m} will only approximate D_{50s} when laboratory sediment mixtures are well-sorted, as there is little potential for **textural** response of a well-sorted bed material. Hence, only under these conditions will τ_{cr50m}^* approximate τ_{cr50s}^* . Potential textural responses are not an issue, however, for incipient motion of laboratory mixtures **defined** from visual observation (τ_{cv50m}^*).

Data from Table 1.1 are plotted in Figure 1.5 stratified by τ_{c50}^* type and incipient motion definition. Based on the above discussion, neither the subsurface dimensionless critical shear stress values (τ_{c50ss}^*) nor the reference-based mixture values (τ_{cr50m}^*) with



<u>Turbulent Flow</u>					<u>Fully Laminar Flow</u>
$D_{50}/h_c \leq 0.2$	▲ τ_{*cr50s}^*	● τ_{*cr50m}^*	○ τ_{*cv50m}^*	□ τ_{*cq50s}^*	▢ τ_{*cv50m}^*
$D_{50}/h_c > 0.2$		● τ_{*cr50m}^*	○ τ_{*cv50m}^*	□ τ_{*cq50s}^*	

Figure 1.5 Composite Shields curve categorized by flow condition, relative roughness, τ_{*c50}^* type, and incipient motion definition.

$\sigma_g > 0.5$ are included. Furthermore, only data derived from time-averaged measures of shear stress are presented due to the potential incompatibility of τ^*_{c50} values determined from time-averaged versus instantaneous shear stress measures (e.g., **Buffington** et al., 1992); the majority of the data in Table 1.1 represent time-averaged shear stresses. The data plotted in Figure 1.5 are also segregated by flow condition [i.e., fully laminar versus (smooth, transitional, or rough) turbulent flow] and relative roughness, defined as the ratio of D_{50} to critical flow depth for incipient motion, h_c . As demonstrated by **Yalin** and **Karahan** (1979) two “Shields curves” are defined for laminar versus turbulent flow conditions over similar Re^*_c values (Fig. 1.5). The **laminar** data generally overlie the turbulent data and define a lower-sloped trend than predicted by Shields (1936) for low Re^*_c values.

Scatter within Shields curves has long been attributed to methodological differences between experiments (e.g., Tison, 1953). However, a systematic examination of such influences has not been previously undertaken. When classified by incipient motion definition clear distinctions within the turbulent flow data are observed (Fig. 1.5). For laboratory sediment mixtures, two distinct sub-parallel Shields curves **are** evident for incipient motion defined by reference transport rate versus visual observation (i.e., τ^*_{cr50m} vs. τ^*_{cv50m} for turbulent flow), with the latter generally underlying the former and suggesting a systematic methodological bias. Although there is considerable scatter, reference values of dimensionless critical shear stress for surface material (τ^*_{cr50s}) with low relative roughness ($D_{50}/h_c < 0.2$) dovetail with those of laboratory sediment mixtures (τ^*_{cr50m}), defining a constant average τ^*_{cr50} value of about 0.06 (fit by eye) for $Re^*_c > 10^3$ (dashed line, Fig. 1.5). This value is identical to **that** originally proposed by Shields (1936) for fully turbulent flow. The surface dimensionless critical shear stress values determined **from** competence equations (τ^*_{cq50s}) define their own space separate **from** the

other data, indicating a third methodological bias. However, the $\tau^*_{c_{q50s}}$ data are too **scattered** and too few to identify any structural similarities with that of the other data (Fig. 1.5).

Closer inspection of Figure 1.5 shows that many of the data cluster into steeply sloping lineaments. This observation has previously been explained by **Bathurst** et al. (1983) as a relative roughness effect. **Bathurst** et al. (1983) demonstrated that for a given median grain **size**, τ^*_{c50} systematically increases with greater relative toughness and that the rate of increase depends on channel slope. Greater form drag caused by increased relative roughness decreases the shear stress available at the bed for sediment transport, resulting in a higher **total shear stress required** for incipient motion, and thus an apparently greater τ^*_{c50} value. It is because of this effect that I have segregated the data in Figure 1.5 by relative roughness. $D_{50}/h_c < 0.2$ was chosen as a value generally representative of gravel-bedded streams. Use of τ' rather than τ_0 in calculating τ^*_{c50} would likely collapse the observed relative roughness lineaments. The effect of bed slope on τ^*_{c50} values in Table 1.1 and Figure 1.5 is insignificant, as most of the data used are derived from experiments with bed **slopes** < 0.01 . The data of **Bathurst** et al. (1987) and **Mizuyama** (1977) are notable exceptions, however τ^*_{c50} values reported for these studies are based on a modified Shields stress that accounts for both bed slope and bulk material friction angle (Table 1.1).

Figure 1.5 is a useful addition to previous compilation studies (i.e., Miller et al., 1977; Yalin and Karahan, 1979). because it includes for the first time reference and competence-based τ^*_{c50} values for surface material ($\tau^*_{c_{r50s}}$ and $\tau^*_{c_{q50s}}$) and demonstrates methodological differences within compiled τ^*_{c50} data sets. The rough, turbulent flow value of $\tau^*_{c50} = 0.045$ previously **reported** by Miller et al. (1977) and Yalin and Karahan (1979) is typical of visually determined mobility thresholds of laboratory **mixtures** ($\tau^*_{c_{v50m}}$), but underestimates dimensionless critical shear stresses determined from

reference transport rates ($\tau^*_{c_{r50m}}$ and $\tau^*_{c_{r50s}}$) (Fig. 1.5). Because the later are based on a less subjective incipient motion definition, they are preferred in this analysis. The competence-based data ($\tau^*_{c_{q50s}}$) are too few and too scattered to interpret at this time and are derived from a variety of subdefinitions of incipient motion (see Table 1.1 notes). In contrast, **the** majority of the $\tau^*_{c_{r50}}$ values for rough turbulent flow and low relative roughness are derived from surface-based studies employing Parker and others' (1982) incipient motion **definition**, adding a certain degree of consistency; it is the rough turbulent flow and low relative roughness portion of the Shields curve that is of significance for surface mobility in gravel-bedded streams. In this region the $\tau^*_{c_{r50s}}$ data with low relative roughness have a range of 0.032-0.087; the 0.032 value is an average of the data reported for Parker and Klingeman (1982), Wilcock and Southard (1988), and Parker (1990). As these values **are** variations of the same data set [that of **Milhous (1973)**] analyzed using Parker and others' (1982) definition of incipient motion.

Assuming similarity of incipient motion definition, the reported range of $\tau^*_{c_{r50s}}$ values can be attributed to neglect of roughness effects (i.e., sidewalls, form drag, etc.) and differences in bed material properties (i.e., grain sorting, packing, shape and rounding). Neglect of roughness effects (i.e., use of τ_0 rather than τ') causes overestimation of $\tau^*_{c_{50}}$. Differences in **bed** material properties can either increase or decrease particle mobility. Greater sorting and angularity cause grains to be **more** resistant to movement and increase $\tau^*_{c_{50}}$ values (Shields, 1936; Miller and Byrne, 1966; Li and Komar, 1986; **Buffington** et al., 1992). In contrast, increased sphericity, looser packing, and surfaces with **protruding** grains increase grain mobility, resulting in relatively lower $\tau^*_{c_{50}}$ values (Fenton and Abbott, 1977; Church, 1978; Reid et al., 1985; Li and Komar, 1986; Kirchner et al., 1990). Because none of the $\tau^*_{c_{r50s}}$ studies fully account for roughness effects (Table 1.1), the lowest $\tau^*_{c_{r50s}}$ value [e.g., the average Milhous value of 0.0321] was selected for use in the threshold channel model: the lowest value likely

represents the least amount of overestimation caused by neglect of roughness elements. A low τ^*_{cr50s} value is also an appropriate choice for natural gravel-bedded rivers as they are typically poorly sorted. It is cautioned, however, that this choice is based on a limited set of τ^*_{cr50s} data, and as such is tentative.

Although the τ^*_{c50} data segregation presented in the above analysis provides some guidance for interpreting the myriad τ^*_{c50} values **reported** in the literature, it is likely that further insight can be achieved by explicitly accounting for bed material properties and roughness effects. It is commonly implied that because flume-based studies of incipient motion employ initially planar bed surfaces they are **free** of form drag influences caused by **bedforms** (e.g., Miller et al., 1977). This is true for the visually-based studies, but it is not so for most of the reference-based investigations, such as Shields' (1936). In the visual studies, flow is typically gradually increased until grains are observed to move from a plane-bed surface (Kramer, 1935; White, 1970; **Yalin** and Karahan, 1979). In contrast, most of the reference transport rate studies are based on **bedload** transport data collected after attainment of equilibrium conditions, which in many instances are characterized by the presence of **bedforms** (cf. Gilbert, 1914; Shields, 1936; Guy et al., 1966; Wilcock and **Southard**, 1988). **Bedform** drag in natural rivers has been estimated as comprising **10-75%** of the total channel roughness (Parker and Peterson 1980; Prestegard 1983; **Dietrich** et al., 1984; Hey **1988**), indicating a **potentially** significant difference between τ' and τ_0 , and hence the calculated τ^*_{c50} value if **bedform** roughness is not accounted for.

Our understanding of incipient motion studies would additionally be greatly improved from standardization of investigative methodology (Wilcock, 1988). Even within the methodological divisions presented here there are subtleties of **definition** that cause some of the observed scatter. For example, Wilcock (1988) has demonstrated that there are slight differences in $\tau^*_{c_{ri}}$ values using the same data but differing definitions of

reference transport rate. Figure 1.5 is only a first-order categorization of τ^*_{c50} data and, strictly speaking, compatibility of τ^*_{c50} values is only assured when identical investigative methods are used. More clarity may also be achieved by using appropriate k_s values when calculating Re^*_c . There have been numerous k_s empiricisms proposed [cf. Einstein and Barbarossa (1952), Leopold et al. (1964), Kamphuis (1974), Hey (1979), Bray (1980), Whiting and Dietrich (1990)], most of which for heterogeneous bed surfaces are greater than D_{50s} . Whiting and Dietrich (1990), for example, suggest $k_s=3D_{84}$. Even for near-uniform sediments, $k_s=D_{50}$ may be inappropriate, as indicated by the discrepancy between boundary Reynolds Numbers for structurally similar portions of Shields' (1936) curve and that of Nikuradse (1933) [see discussion by Yalin and Karahan (1979)]. As is commonly done in engineering practice, k_s should be defined relative to Nikuradse's (1933) results as an equivalent (Nikuradse) sand grain roughness, providing a common reference frame amongst incipient motion studies.

Chapter 2: Investigation of the Threshold Channel Model and Examination of Textural Response to Sediment Supply

APPLICATION OF EXISTING DATA SETS TO THE GENERAL MODEL

In order to investigate the general validity of the **bankfull** threshold **channel** model a literature search was conducted to **find** all available paired data of median surface grain **size** and **bankfull** shear stress. Four hundred thirty six data points from 14 studies representing a wide range of channel sizes and types located throughout the United States, Britain, Ireland, India, and Canada are plotted in Figure 2.1. The data from sand-bedded **channels** ($D_{50s} < 2$ mm, circles) segregate from the gravel- and cobble-bedded streams (Fig. 2.1) due to basic differences between live-bed and threshold channels. Sand-bedded channels exhibit live-bed transport, **with** mobility occurring at most stages. As such, D_{50s} predicted from a **bankfull** threshold of mobility should be a considerable overestimation. Furthermore, sand-bedded channels typically have closer-spaced and multi-scale bedforms, causing potentially greater relative **bedform** roughness (e.g., τ_f/τ_0) **than** in gravel-bedded channels. Consequently, live-bed channels should have lower relative **bed** shear stress (e.g., τ/τ_0) and hence smaller grain sizes. The strong separation of the sand-bedded data from both the coarse-grained data and the **bankfull** threshold prediction (Fig. 2.1) is thus likely due to a mobility threshold significantly less than **bankfull**, as well as potentially greater relative **bedform** roughness. This separation of data reinforces fundamental differences between live-bed and threshold channels.

The **bankfull** threshold channel prediction of D_{50s} using $\tau^*_{c50s} \approx 0.032$ is shown by the solid black line in Figure 2.1. According to the hypotheses presented in Chapter 1, the median surface grain sizes of coarse-grained channels should plot on or below **the** threshold prediction, depending on **the** degree of textural response. Median surface grain

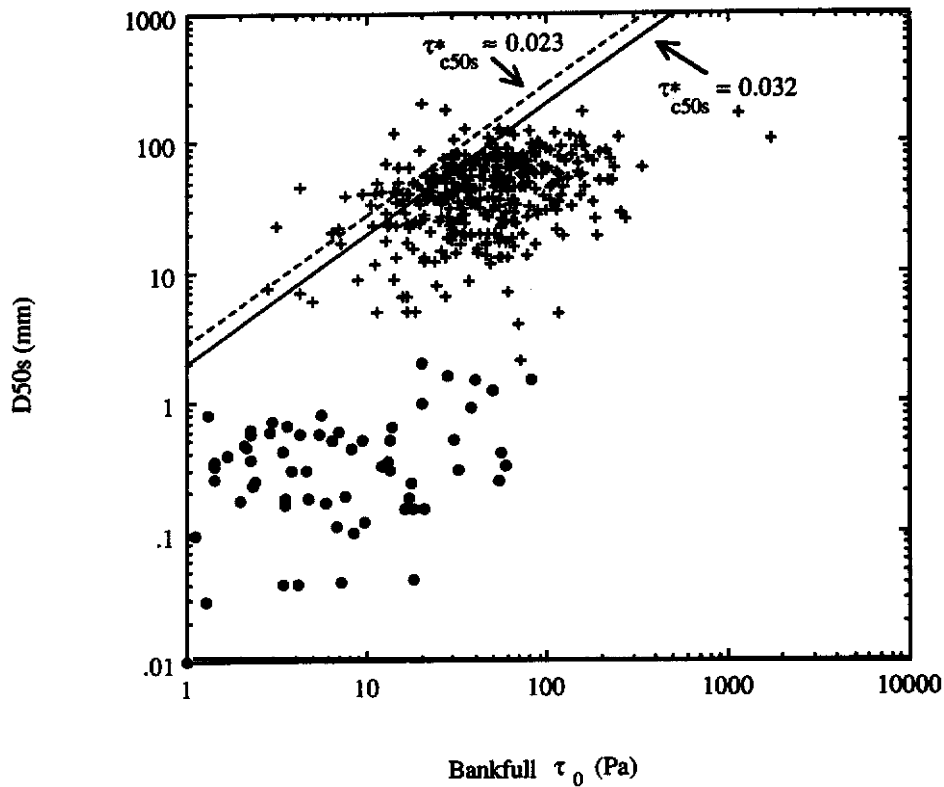


Figure 2.1 Published τ_0 and D_{50s} data compared with the threshold model prediction, assuming $\tau^*_{c50s}=0.032$ (solid line). Channels with $D_{50s} \leq 2$ mm are defined as sand-bedded (i.e., live-bed) channels (\bullet), distinguished from gravel- and cobble-bedded (i.e., threshold) streams ($+$). Data are from natural channels and irrigation canals studied by: Lane and **Carlson** (1953); Brush (1961); Simons and Albertson (1963); **Chitale** (1970); Thome and **Lewin** (1979); Lisle (1979); Andrews (1984); **Florsheim** (1985); Hey and Thome (1986); Higginson and Johnston (1988); Kinerson (1990); Lisle and Madej (1992); Smith and **Buffington** (in press); and present study.

sires that plot above the threshold **prediction** imply sediment immobility at **bankfull** stages. While the bulk of the data lie on or below the solid prediction line, there are a fair number of points above it. Rather than being immobile, an alternative explanation for these upper data is that my choice of τ^*_{c50s} is too high. A lower τ^*_{c50s} value would raise the **D_{50s}** prediction line, capturing some of the upper data. These upper data exhibit a plateau, indicated by a decline in the density of points at larger grain sizes. A line fit by eye to this plateau corresponds with a τ^*_{c50s} value of about 0.023 (dashed line, Fig. 2.1). If these data are reliable, then $\tau^*_{c50s} \approx 0.023$ presumably represents the natural upper limit of competence for a given **bankfull** shear stress in coarse-grained channels. In other words, the least sorting and angularity, the greatest protrusion and sphericity, and the least amount of other hydraulic roughness found in natural, coarse-grained channels; consequently maximizing **D_{50s}** for a given **bankfull** shear stress.

Because the data presented in Figure 2.1 are **synthesized** from many different studies, potentially employing slightly different data collection methods, there is some danger in making this empirical fit. It is unlikely that slope is a significant source of error, because most of the studies measured slopes over reasonably long reaches. **Admittedly**, recognition of **bankfull** geometry can be problematic (Williams, 1978). Personal experience, however, suggests that field-oriented investigators are usually in agreement about **bankfull** location; thus, little error is attributed to reported shear stress values. The largest potential source of error is likely due to differences in grain **size** sampling techniques. Accurate representation of bed grain sizes depends on the sampling strategy employed; as will be seen in Chapter 3, a single sample of limited **areal** extent can be an extremely poor representation of reach-average grain size in natural **coarse-grained** streams, as such channels are typically composed of complex and diverse textural patches. Because the grain **size** sampling error is unknown for the data presented in Figure 2.1, $\tau^*_{c50s} \approx 0.032$, rather than $\tau^*_{c50s} \approx 0.023$, will be retained for the **bankfull** threshold channel

prediction of D_{50s} . The empirical plateau at $\tau^*_{c50s} \approx 0.023$ is nevertheless intriguing, warranting further, more carefully constrained **research** of the natural lower limit of τ^*_{c50s} and the upper limit of competence in coarse-grained Channels.

Median surface grain sizes that plot on and just below the threshold **channel** prediction are **hypothesized** to represent low sediment supply, armored, plane-bed channels in which bed and banks provide **all** of the hydraulic roughness. Increased sediment supply or the introduction of other roughness elements is expected to cause textural **fining** and deviation from the prediction. Within this framework, Figure 2.1 indicates that **textural** response is common in coarse-grained channels; the data do not collapse into a single trend, but rather span about an order of magnitude of median surface grain sizes for a given shear stress.

Further examination of Figure 2.1 shows that beyond shear stresses of about 70 Pa in coarse-grained channels there is a decrease in the range of median surface grain sizes and a general lack of data around the threshold prediction line. Assuming that the plotted data for channels with depth-slope products in excess of 70 Pa are typical, then there is presumably some characteristic change in sediment supply or hydraulic roughness for these channels, as was suggested for the sand-bedded rivers. Since the magnitude of total boundary shear stress is generally dominated by slope, the channels with shear stresses in excess of 70 Pa are likely to be steep gradient plane-bed **channels**, approaching cascade and step-pool morphologies in the terminology of Montgomery and Buffington (1993). Although steep-gradient channels **are** characteristically high energy environments, much of the available shear stress is turbulently dissipated by tumbling or jet-and-wake flow caused by individual large grains or grain clusters. Consequently energy dissipation characteristic of steep-gradient **channels** may lead to smaller median surface grain sizes due to less available bed shear stress and may explain the leveling-off of median surface grain sizes observed in Figure 2.1.

TEXTURAL RESPONSE TO SEDIMENT SUPPLY

Several data sets exist that can be used to examine textural response to sediment supply within the framework of the **bankfull** threshold channel model. Flume experiments by Kuhnle and **Southard** (1988) and **Dietrich** et al. (1989) both **document** surface **fining** of laboratory plane-bed channels with increased sediment loads. Both studies found that low sediment supplies produced armored beds, while extreme sediment loading created surface textures similar to the **size** distribution of **the** supplied sediment ($q^*=1$). Within the threshold model framework the low sediment supply armored beds from these two studies plot close to the threshold channel prediction line and have lower q^* values (Fig. 2.2), while increasing sediment supply produces finer surface textures that progressively deviate from the threshold prediction and have higher q^* values. Thus with increasing sediment load there is a systematic surface textural fining and deviation from the **bankfull** threshold channel prediction.

As mentioned previously, textural response to sediment supply within the threshold model construct is simply another way to express the q^* theory. By definition a q^* of 0 corresponds with the threshold channel prediction. However, because the surface and subsurface critical shear stresses are back-calculated from Shields' equation [i.e., (2)] the resultant q^* values depend on the τ^*_{c50s} value used, as illustrated by Figures 2.2a and 2.2b. Furthermore, while the magnitude of q^* increases with deviation from a given threshold prediction, the gradient of q^* values with this deviation depends on the ratio of τ_0/τ_{c50ss} [i.e., (6)]. For example, because τ_0/τ_{c50ss} is different in the two flume studies (**Dietrich** et al., 1989), their q^* values are not necessarily the same for similar deviations from the threshold prediction: in the study by **Dietrich** et al. (1989) a q^* value of 1 is approached with significantly less deviation from the threshold prediction (Fig. 2.2). The

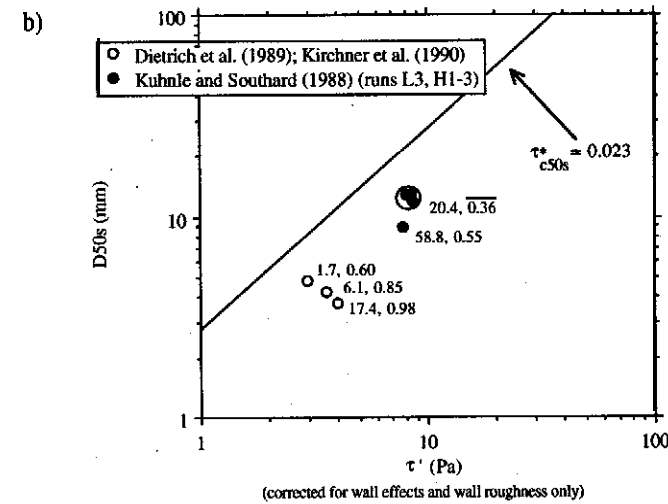
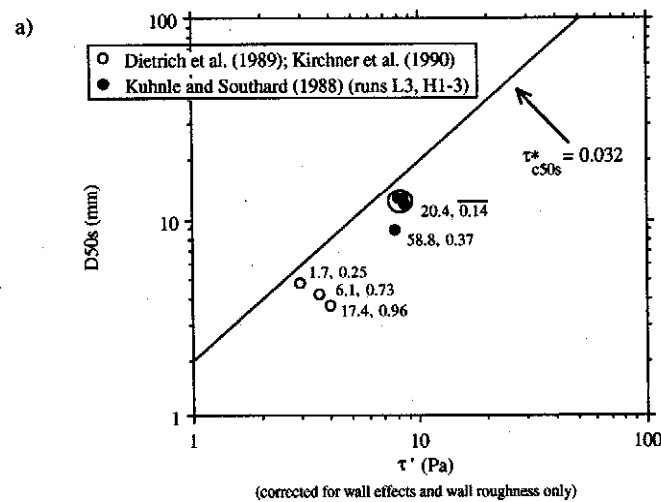


Figure 2.2 Systematic deviation of D_{50s} from the threshold model prediction [a) $\tau^*_{c50s}=0.032$, b) $\tau^*_{c50s}=0.023$] as a function of increasing sediment volume supplied to laboratory plane-bed channels. τ' is the cross-sectionally-averaged total boundary shear stress corrected for sidewall effects using the method of Shimizu (1989), assuming a bed roughness 100 times that of the flume walls (see also discussion of sidewall effects in Chapter 3 Methods and Fig. 3.4 caption). Numbers next to plotted points are sediment feed rates (g/min-cm) followed by q^* values calculated from (6) with $\tau_0=\tau'$ and $\tau_{c50}=\tau^*_{c50s}(\rho_s-\rho)gD_{50}$, assuming $\rho=1000$ kg/m³ and $\rho_s=2650$ kg/m³; τ_{c50s} and τ_{c50ss} values are calculated using respective median grain sizes of the bed surface material and sediment feed as reported by Kirchner et al. (1990, Table 2) and Kuhnle and Southard (1988, Figs. 2 and 14). Only data from plane-bed morphologies are plotted; **bedload** sheets (Whiting et al., 1988) within plane-bed channels are considered unobtrusive “bedforms.”

ratio of τ_0/τ_{c50ss} is the theoretical critical shear stress of a **fully** armored channel relative to that of a completely **unarmored channel**. As such, this ratio expresses the theoretical potential for textural response, with lower values indicating less response potential. For a given depth-slope product the ratio of τ_0/τ_{c50ss} is largely a function of the imposed sediment supply distribution. Consequently the gradient and lower limit of textural response (D_{50ss}) expressed by **the q^*** theory cannot be predicted theoretically, because the input sediment supply distribution at any given point in a channel network is a stochastic function of basin geology, geomorphology, and climate; D_{50ss} and the ratio of τ_0/τ_{c50ss} must be determined by field investigation. While the ratio of τ_0/τ_{c50ss} provides an indication of a channel's overall potential for textural change, the current degree of textural response to sediment supply must be evaluated by other means, such as cl^* .

Once textural fining has occurred in response to increased sediment supply a channel no longer exhibits **bankfull** threshold mobility, as smaller D_{50s} values imply a lower threshold of mobility. It is hypothesized that extreme textural response to sediment supply can create mobility thresholds low enough that the channel begins to behave more like a live-bed channel (e.g., Reid and others' (1985) Turkey Brook site discussed in Chapter 1). However, extreme changes in sediment transport characteristics of this sort depend on the ratio of τ_0/τ_{c50ss} . For example, a low τ_0/τ_{c50ss} ratio limits the range of textural fining and thus the range of critical shear stresses, while for a high ratio of τ_0/τ_{c50ss} there is a much broader range of both potential textural fining and corresponding critical shear stresses. Consequently channels with high τ_0/τ_{c50ss} ratios are more likely to behave like live-bed channels in response to extreme sediment loading. High τ_0/τ_{c50ss} ratios can be natural or induced by management activities, such as road building **and** use, that increase the proportion of **fine** sediment supplied to a channel (e.g., Reid and **Dunne, 1984**), hence lowering D_{50ss} and τ_{c50ss}

Kinerson (1990) documented sediment-induced textural **fining** in natural **channels** in northern California and validated the use of cl^* as an indicator of sediment loading. He examined channels with a variety of sediment loading conditions and chose sample sites in straight sections of the channel with low-amplitude **bedforms** and away from m-channel obstructions. Sample sites were chosen in this fashion so as to **minimize** hydraulic roughness other than grain roughness. He found that **channels** with low sediment supplies had low q^* values, while sediment-impacted **channels** had q^* values near 1. With the exception of one point, **Kinerson's** (1990) data show the same systematic deviation of surface textures from the threshold channel prediction with increasing q^* and hence sediment supply (Fig. 2.3). However, the sediment loading conditions inferred from **Kinerson's** (1990) q^* values were substantiated in some cases by fairly qualitative assessments of sediment supply.

Application of results from a study by **Lisle and Madej** (1993) imply that q^* was not a good indicator of sediment loading in a comparison of **aggrading** (high sediment supply) and degrading (low supply) reaches of a northern California stream. **Lisle and Madej's** (1993) negative results may **be** due to neglecting differences in **bedform** roughness between the two study reaches.

With q^* as a surrogate for sediment loading, the field and laboratory studies discussed above are combined in Figure 2.4 in order to emphasize the systematic textural **fining** and deviation from the threshold channel prediction of **median** surface grain size with increasing sediment supply. These data show that textural **fining** in response to sediment supply can be quite significant, resulting in a minimum ratio of observed-to-predicted **D_{50s}** of about 0.1, or a ten-fold decrease in **D_{50s}**. Figure 2.4 also demonstrates that similar q^* values can correspond to different magnitudes of textural fining, where fining is expressed as the ratio of observed-to-predicted median surface grain **size**. At low sediment supplies

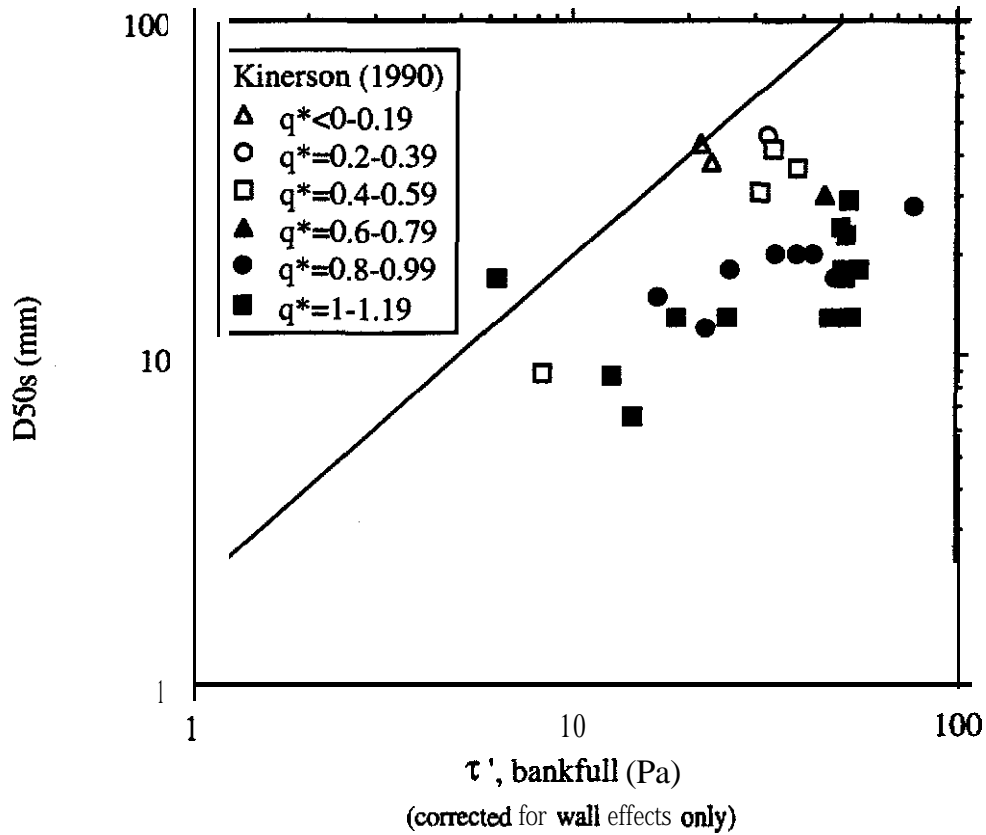


Figure 2.3 Textural fining and deviation of D_{50s} from the threshold model prediction as a function of increasing sediment supply in natural gravel-bedded channels. τ' is the cross-sectionally-averaged total boundary shear stress corrected for sidewall effects using the method of Shimizu (1989), assuming uniform bed and bank roughness length scales. q^* values are determined with $\tau'_{c50s} = 0.032$ as per Figure 2.2 caption.

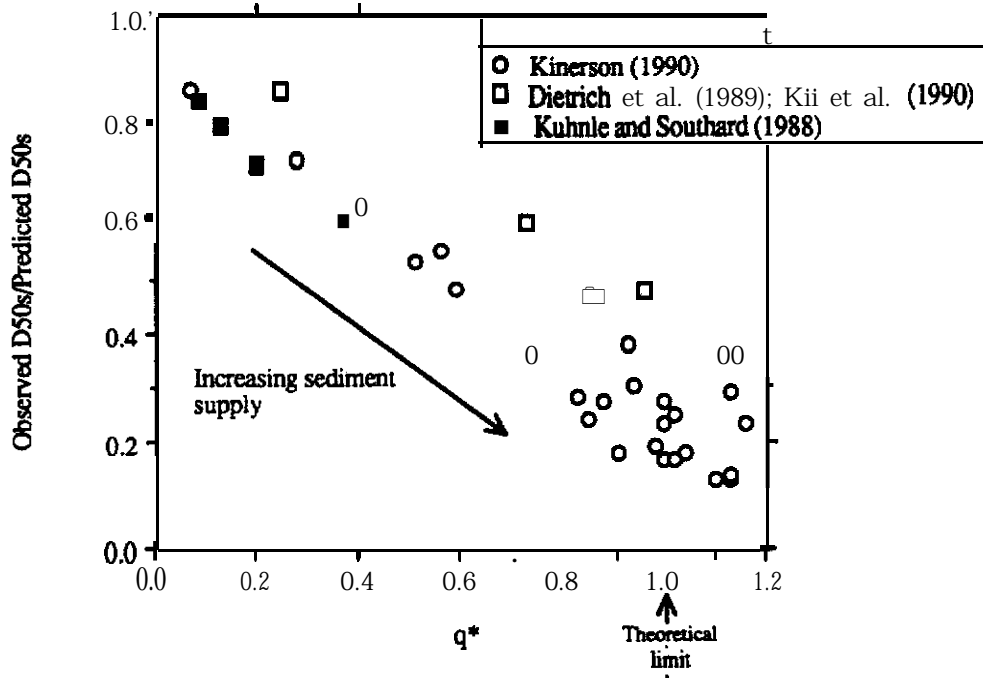


Figure 2.4 q^* versus the ratio of observed-to-predicted D_{50s} in both natural and laboratory channels. The ratio of observed-to-predicted D_{50s} is inversely related to q^* , and thus sediment supply. The D_{50s} ratio is not unique for specific q^* values, having a range of up to 0.3 units for a given q^* .

(i.e., q^* near **zero**) the ratio of observed-to-predicted **D_{50s}** is close to one in natural channels, indicating that the **bankfull** threshold model accurately predicts the median grain **size** of a fully armored channel. The **bankfull** threshold model thus provides a **significant** contribution to the q^* theory in that it defines the critical shear stress corresponding to the limit of textural coarsening in gravel-bedded channels. As originally proposed (Dietrich et al., **1989**), the q^* equation did not specify a characteristic boundary shear stress; that is, q^* was expressed in terms of a generic boundary shear stress, rather than in terms of the **bankfull** boundary shear stress, **τ_0** , as in (6).

Although previous investigation of the q^* theory has been **limited**, results from such studies generally validate its use as an indicator of **sediment** supply, provided that other roughness effects are accounted for. This latter point is an important clause that Kinerson (1990) recognized, but that has not been fully explored. Surface textural response due to hydraulic roughness in forest gravel-bedded streams is examined in the next chapter and a preliminary analysis of relative magnitudes of influence caused by sediment supply and hydraulic roughness is presented. These results provide some insight into typical ranges of roughness correction necessary for q^* analyses in forest channels.

Chapter 3: Field Study of the Effects of Hydraulic Roughness on **Gravel-bed** Surface Textures

A field study of forest gravel-bedded rivers was conducted in order to **document** textural response to other types and scales of hydraulic roughness. Detailed morphologic information was collected, but the principal intent was a reach-average comparison of textural response in channels **characterized** by distinctly different roughness elements. Investigation of in-channel roughness features was limited to roughness caused by bed surface particles, bedforms, and LWD. Three distinctly different channel types were examined that showed increasing complexity of roughness: plane-bed channels; pool-riffle channels with minimal amounts of **LWD**; and LWD-rich **pool-riffle** channels (Fig. 3.1). These three channel types represent a progressive cumulation of particle, **bedform**, and LWD roughness.

Forty-one gravel-bedded channels were studied in forest environments of northwestern Washington and southeast Alaska. Infrequent, catastrophic sediment inputs from hollow failures and resultant debris flows are **characteristic** of this steep, mountainous terrain. Although sediment loading of the study sites was not **quantified**, channels exhibiting evidence of recent catastrophic sediment impacts were avoided. Evidence for such impacts includes: recent landslide tracks **entering** a channel; fresh debris flow levees, and riparian vegetation inundated by debris flow deposits; in-channel LWD that is predominantly buried by alluvium; pools with low residual depths and largely filled by **fine** sediment (Lisle and Hilton, 1992); bar-riffle topography conspicuously lacking pools; wide, shallow channels with width-to-depth ratios anomalously larger than adjacent upstream and downstream reaches and in some instances accompanied by braiding; and riffles covered by extensive sand stripes and drapes (Lisle and Hilton, 1992). Evidence for

a1)



a2)

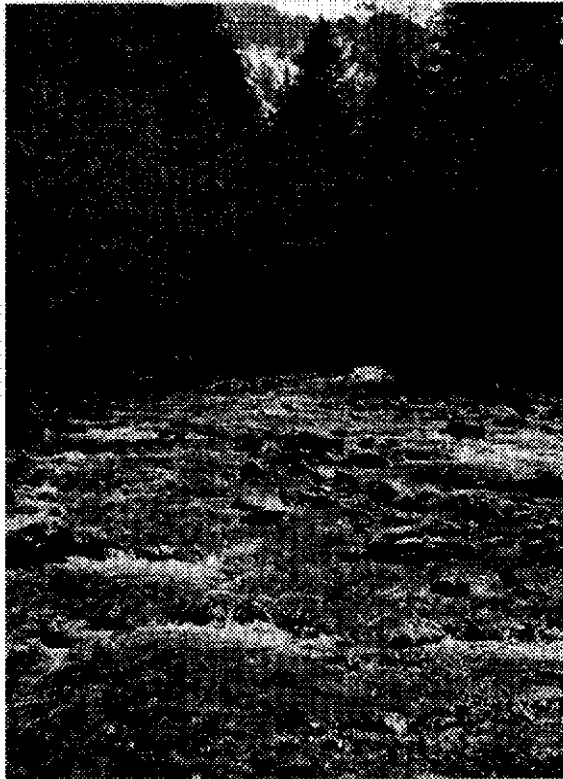
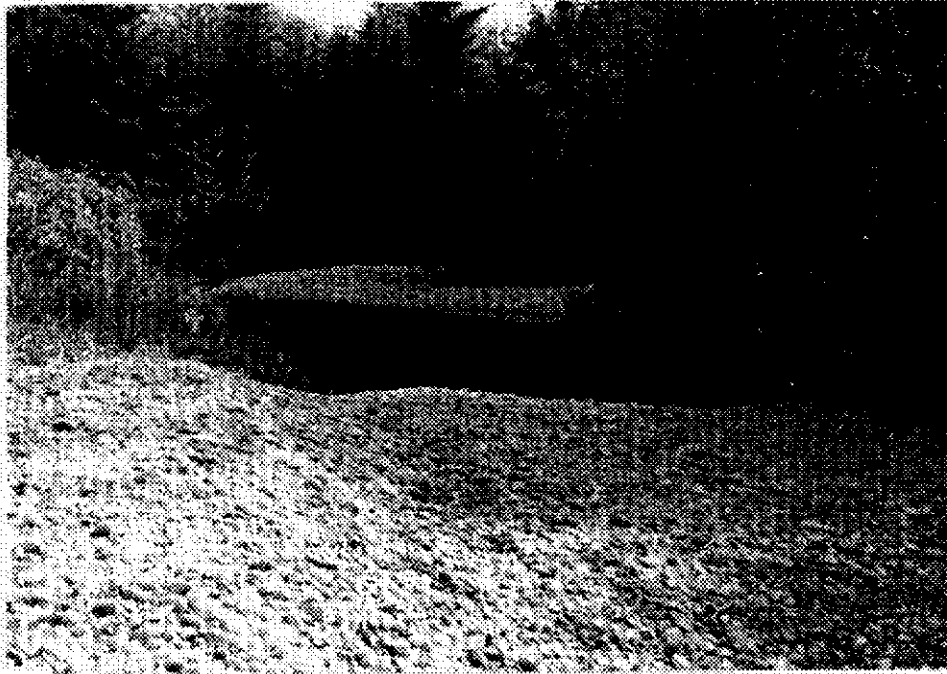


Figure 3.1 Photographs of typical a) plane-bed, b) LWD-poor pool-riffle, and c) LWD-rich pool-riffle forest channels of the Pacific Northwest and southeast Alaska.

b1)



b2)

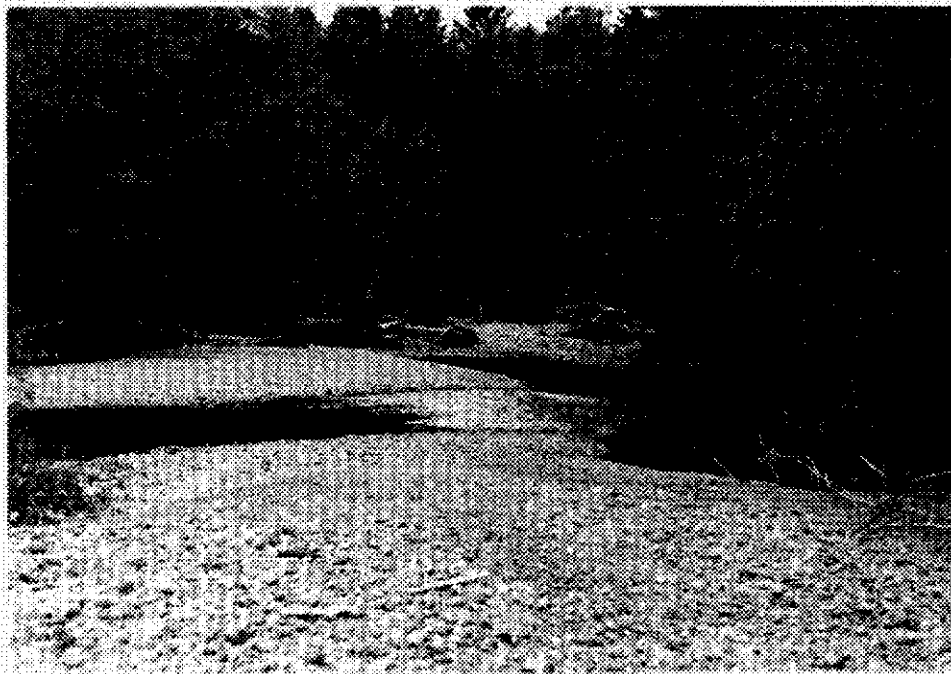


Fig. 3.1 cont.

c1)



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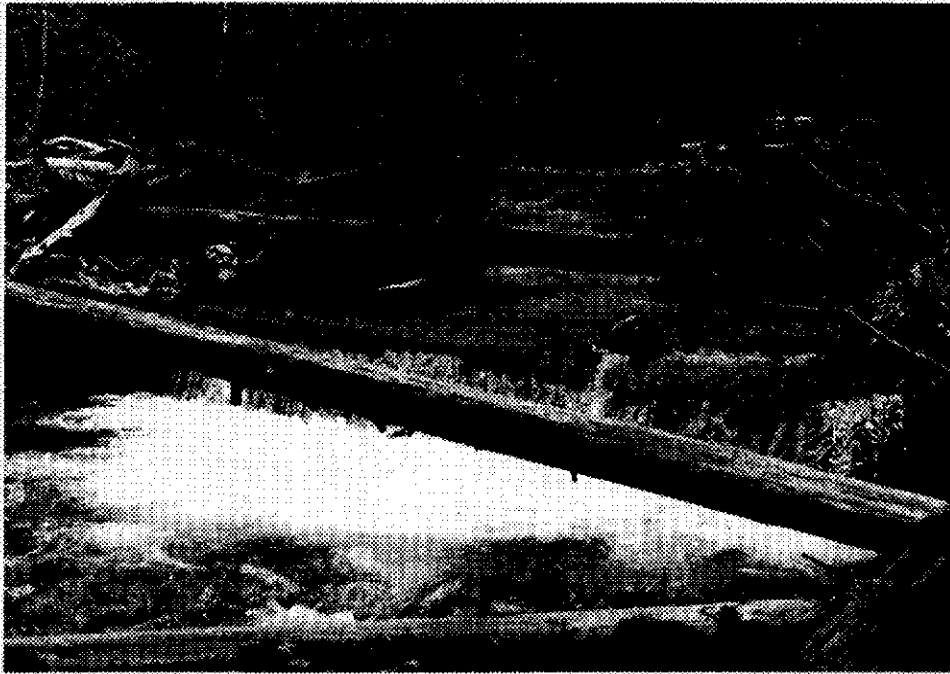


Figure 3.1 cont.

significant sediment impacts of this sort was only observed in five of the forty-one study sites. Levels of sediment loading at the **remaining** sites was likely variable, but not orders of magnitude different. The sediment-impacted channels, however, will be given special consideration in the following analysis.

STUDY SITES

Fourteen channels were studied on the Olympic Peninsula of northwestern Washington (Fig. 3.2). The Peninsula is characterized by mountainous terrain and a coastal rain forest of Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), red cedar (*Thuja plicata*), and Douglas fir (*Pseudotsuga taxifolia*). Bedrock geology of the Peninsula is predominantly composed of marine basalts and sediments of Eocene to Miocene age accreted onto the North American plate (Tabor and Cady, 1978a; b). The Peninsula is divided into two **terrains**: the peripheral rocks, interlayered marine basalts and sediments forming an easterly concave arc believed to have resulted from subductive accretion pinned between older terrains of Vancouver Island and the Cascades (Tabor, 1975); and the core rocks, **accreted** lithic assemblages of predominantly marine sediments that have been sheared, folded, and metamorphosed to varying degrees within the **confine** of the basaltic peripheral rocks (Tabor and Cady, 1978a; b). All of the Olympic channels surveyed in the current study lie in watersheds influenced by Pleistocene glaciation (either alpine or continental) and are typically incised into fluvioglacial deposits. The northern study channels flow through an area exposed to repeated advances and retreats of continental ice. Lithologies associated with each channel **are** listed in Table 3.1, based on mapping by Tabor and Cady (1978a).

Logging activity on the Olympic Peninsula is generally intensive, with some forests on their third rotation. Due to recent progressive management practices most study sites

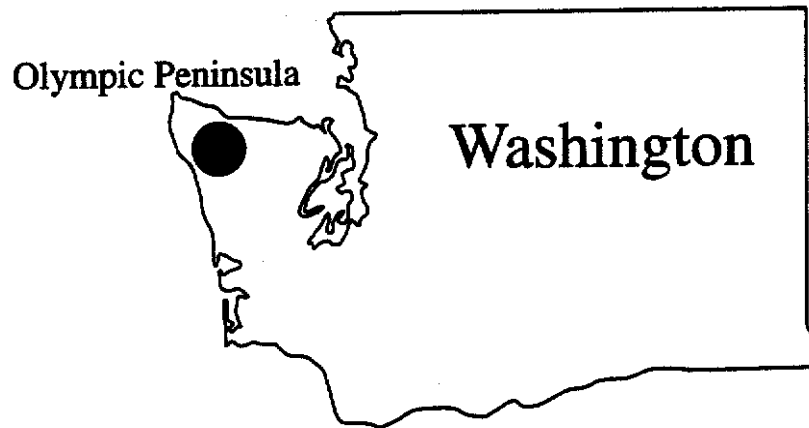


Figure 3.2 Location map of the Olympic study sites.

TABLE 3.1: Rock Types Associated with Olympic Study Sites

	Proximal to channel	Headwaters
<i>Channel</i>		
Lower Dry Creek	1	5
Upper Dry Creek	1	5
Alder Creek	1	4
Lower S Fork Hoh Slough	1	3, 4, 5
Upper S Fork Hoh Slough	1	3, 4, 5
Lower Pins Creek	1	1
Upper Pins Creek	1	1
Cedar Creek	1	1
Hoko River	2	4, 6, 7
Hoko Tributary	2	4
Lower Skunk Creek	2	4
Upper Skunk Creek	2	4
Flu Hardy Creek	2	4
Mill Creek	4	4

Key:

- 1) Pleistocene alpine glacial deposits of gravel, sand, silt, and clay.
- 2) Pleistocene glacial gravels, sand, silt, and clay deposited **from** continental ice sheets. Characterized by xenolithic **clasts**.
- 3) Sandstone and conglomerate [undifferentiated Tur unit of **Tabor** and Cady (1978a), Eocene(?) to Miocene (?)].
- 4) Sandstone and conglomerate [**Tabor** and Cady's (1978a) Two unit of Western Olympic Lithic Assemblage, Eocene to Oligocene].
- 5) Slate and Phylite (**Tabor** and Cady's (1978a) Twos unit of Western Olympic Lithic Assemblage).
- 6) Eocene sandstone and siltstone [unnamed Tusb **unit** of **Tabor** and Cady (1978a)].
- 7) Eocene basalt [**Tcb** unit of Crescent Formation (**Tabor** and Cady (1978a))].

had riparian buffers composed of mixed shrub and conifer, however some study sites had been clear cut to channel margins, resulting in riparian forests of mixed shrub and red alder (*Alnus rubra*). Coniferous buffers **were** typically not pristine old growth, indicating a long history of management disturbance. **Hillslope** failures are common in the Peninsula and **are** attributed to timber harvesting and subsequent reduction of root strength in topographic hollows. Relict debris flow deposits form channel-margin terraces in one of the pool-riffle channels studied and indicate both long **runout** paths and the potential for periodic large sediment inputs. A more recent debris flow **disturbed** one of the plane-bed channels, leaving riparian vegetation inundated with alluvium. Most of the channels studied had banks composed of fluvio-glacial clays, silts, sands, and gravels, providing a readily accessible sediment source.

The Olympic data were further supplemented by data from 27 coastal channels of the southeast Alaskan Alexander Archipelago (Fig. 3.3). These data were collected by the US Forest Service as part of a morphologic comparison of pristine and heavily disturbed watersheds (Smith and **Buffington**, in press). An important difference between the two land use types investigated in southeast Alaska is that the pristine channels were characterized by high LWD loading, while the disturbed channels were generally clear cut to the stream banks and had most or all of their in-channel LWD removed. The Alaskan channels are of particular relevance to the current study because of the spectrum of LWD loading that they provide, and thus the potential range of textural response. The majority of the Alaskan channels are pool-riffle-type, but four of them are transitional between **pool-riffle** and plane-bed. Two of the study sites are downstream of recent large landslides. One other study site has also had recent landslide input, but of a lesser magnitude.

The southeast Alaskan study **areas** are characterized by steep glaciated terrain, maritime climate, and rain forests predominantly composed of Sitka spruce (*Picea*

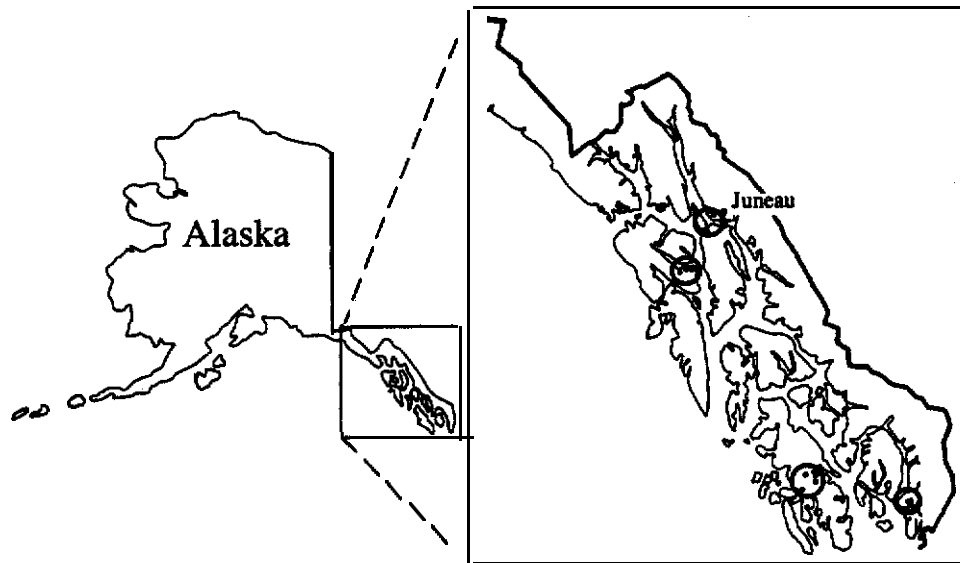


Figure 3.3 Location map of the southeast Alaskan study sites.

sitchensis) and western hemlock (*Tsuga heterophylla*). Hillslopes are commonly grooved by avalanche chutes and hollow **failures**. The geology of southeast Alaska is **characterized** by all major rock types of ages ranging from Proterozoic(?) to **Quaternary** (Gehrels and Berg, 1992), largely accreted during the **Cretaceous** to **Eocene** (Goldfarb et al., 1988; Gehrels et al., 1990). Lithologies associated with study sites are listed in Table 3.2, based on generalized mapping by Gehrels and Berg (1992) and personal observation. Many of the waterways of the Alexander Archipelago are fault controlled and were previously occupied by massive glaciers. The entire Archipelago was profoundly influenced by Pleistocene glaciation, with only the highest peaks exposed during the glacial maximum (Reed, 1958). Isostatic rebound following glacial retreat continues today and emergent marine terraces are common. Unlike the Olympic channels, however, the Alaskan study sites are devoid of glacial deposits.

METHODS

Olympic Study Sites

Bankfull channel widths were measured at 10 m intervals in order to iteratively establish reaches that were ten channel widths long. Average **bankfull** geometries were determined from surveys of three cross sections per reach, and a center-line survey of bed topography was used to approximate the energy slope. For each of the study sites detailed topographic, textural, and LWD maps were constructed using a total station digital theodolite. Bed topography was contoured **with Surfer®**; various contouring techniques, search patterns, and search radii were tested, with the most accurate representation of channel topography produced from a Kriging technique. Mapped surface textures were used to determine spatially averaged grain size characteristics of each reach and to relate textural patterns to bed topography and LWD.

TABLE 3.2: Rock Types Associated with Southeast Alaskan Study Sites

<i>Channel</i>	<i>Basin Geology</i>
12 Mile Creek 1	pre-Ordovician metasediments and metavolcanics
12 Mile Creek 2	"
Maybeso Creek 1	Silurian to Ordovician sediments and volcanics
Maybeso Creek 2	"
Maybeso Creek 3	"
Maybeso Creek 4	"
Cable Creek	Silurian to Ordovician volcanics
Fubar Creek 1	Silurian to Ordovician sediments and volcanics
Fubar Creek 2	"
Indian Creek	Silurian to Ordovician volcanics
Muri Creek	Devonian volcanics and (?) Silurian syenite and trondhjemite
Bambi Creek	Cretaceous granodiorite and Devonian and Ordovician sediments and volcanics
Upper Weasel Creek 2	Cretaceous to Permian sediments and volcanics
Lower Greens Creek	Triassic to Ordovician sediments and volcanics
Hook Creek	Devonian to Ordovician sediments and volcanics (dacite with phenocrysts of cruciform amphibole) and (?) Silurian syenite and trondhjemite
Trap Creek 1	Silurian carbonates
Trap Creek 2	"
Trap Creek 3	"
Trap Creek 4	"
Trap Creek 5	"
Trap Creek 6	"
East Fork Trap Creek 1	"
East Fork Trap Creek 2	"
Fowler Creek 1	Cretaceous to Jurassic sediments
Fowler Creek 2	"
Lower Fish Creek	Cretaceous to Jurassic sediments and volcanics
Upper Fish Creek	"

Initial reconnaissance of each **stream** was conducted to visually **identify** and partition surface textures. Textures were differentiated according to the method used by **Kinerson** (1990) and Collins (unpub.), which involves identifying the characteristic grain size(s) of a given patch according to approximate standard grain **size** divisions [i.e., Wentworth (1922) as modified by Church et al. (1987)]. For example, patches might be distinguished as: sand and gravel; gravel and small boulder; cobble, gravel, and sand, etc. In my particular application the order of the adjectives used to describe a patch indicates the visual abundance. Transitions between textures are often quite subtle, but resultant mapping error is believed to be small. **After** surface textures **were** visually partitioned a random pebble count of 100 grams (**Wolman**, 1954) was conducted over one or more of each identified textural type. Sampling of every textural patch was prohibitive due to complexity of their spatial distribution within a given channel. Consequently a single pebble count was generally conducted for each textural type and **assumed** representative of other visually similar **textural** patches. Error associated with this assumption was examined in some channels by sampling several textural patches of the same type. Sampled patches were chosen randomly, and the entire area of a given patch was covered in the sampling.

Subsurface sampling was also conducted in order to establish theoretical limits of textural fining as expressed by the q^* theory. Samples were collected from a 1 m^2 area within textural patches that had been pebble counted. The surface layer was excavated by hand and shovel to a depth equal to or greater than the surface **D₈₄** (Church et al., 1987). and the underlying material was dry sieved to determine the subsurface grain size distribution. It is commonly accepted that subsurface bulk sieving is a sampling technique equivalent to pebble counting (**Kellerhals** and Bray, 1971; Diplas and Sutherland, 1988), allowing direct comparison of surface and subsurface samples.

Several studies have been conducted to determine the volume of material needed to adequately represent the subsurface grain size distribution (Church et al., 1987; Diplas and

Fripp, 1992; Wolcott and Church, 1991), with the common statistical requisite that the sample should be large enough to capture the relatively fewer coarse grains, but not be biased by those large grains. Church et al. (1987) proposed that a good representation of the subsurface grain **size** distribution was achieved when the largest **clast** comprised 0.1% of the sample weight; however, they recognized that for coarse material the requisite sample volume would be enormous and suggested a 1% criterion. Because a field scale was unavailable I employed a sampling technique using fixed volumes in which 1 to 3 10 ℓ buckets were sampled depending on the maximum surface grain size, D_{max} , of a given textural patch. Assuming equivalence of surface and subsurface grain size ranges, D_{max} was used to estimate the requisite subsurface sample volume using the following ranges:

$$\begin{aligned} 10 \ell: D_{\text{max}} &\leq 58 \text{ mm} \\ 20 \ell: 58 \text{ mm} &< D_{\text{max}} \leq 73 \text{ mm} \\ 30 \ell: D_{\text{max}} &> 73 \text{ mm} \end{aligned}$$

where D_{max} values of 58 and 73 mm respectively represent 1% of the weight of 10 and 20 ℓ volumes assuming spherical grains of $\rho_s=2650 \text{ kg/m}^3$ and a **voidless** sample volume. For ideal samples of this sort, the weight percent of D_{max} is $\leq 1\%$, but $>1\%$ for 30 ℓ samples with $D_{\text{max}} > 83 \text{ mm}$, as 30 ℓ was the maximum sample **volume** collected regardless of D_{max} . The 1 m^2 sample area was divided into three strips perpendicular to channel flow and one strip was randomly sampled for the first 10 ℓ bucket. Subsequent 10 ℓ volumes for a given sample were collected in an analogous fashion but from progressively greater depths. Each 10 ℓ sample was analyzed separately to examine grain size variation with **depth**.

Initially each 10 ℓ volume was field sieved by hand using standard, square-mesh, 8" diameter sieves. Samples were sieved in half phi intervals and grain sizes less than 8 mm were split according to ASTM (1985) standards and taken for further laboratory

sieving. Grain weights of **clasts** between 8 and 45 **mm** were determined in the field by volume displacement in a graduated cylinder, assuming $\rho_s=2650 \text{ kg/m}^3$. This method is based on a technique developed by Booth et al. (1991). Samples of grains weighed in this fashion were taken for laboratory analysis to determine true densities in order to correct field estimates of weight. Weights of grains larger than 45 **mm** were calculated from intermediate diameter measures, assuming a spherical grain shape with $\rho_s=2650 \text{ kg/m}^3$. Subsurface sampling conducted later in the field season involved collection of whole 10 ℓ samples for subsequent laboratory analysis. In the laboratory, grains larger than 45 mm were separated by hand and binned at half phi intervals based on intermediate diameter measures. The **remaining** sample was dry sieved at half phi intervals using a Ro-Tap@ shaker. All grain weights were measured to 0.1 g using a standard, pad-sensor, laboratory scale.

Reach-average depth-slope products of both the Olympic and Alaskan sites were corrected for wall effects using theoretical findings of **Shimizu** (1989). Wall effects are examined in the current analysis purely as a function of channel geometry, assuming a uniform roughness of bank and bed material. Channel geometry significantly affects boundary shear stress distribution and average flow velocity (**Lundgren** and Jonsson, 1964; Williams, 1970; Hey, 1979; Knight, 1981; Knight et al., 1984; Flintham and Carling, 1988; **Shimizu**, 1989). For obstruction-free, straight, plane-bed channels with large width-to-depth ratios, flow is commonly assumed to be two dimensional and shear stress at the bed is well approximated by the total depth-slope product. Turbulence caused by momentum differences between the channel center and margins causes flow to become progressively more three dimensional for increasingly lower width-to-depth ratios, effectively transferring a portion of the total boundary shear stress to the channel walls (**Parker, 1978b**) and reducing the accuracy of the depth-slope product to approximate bed

shear stress. In practice, wall effects are assumed negligible for $W/h \geq 11-13$, for which case bed shear stresses are approximately 90% of the depth-slope product (Flintham and Carling, 1988). Wall effects are more formally assessed in this analysis through graphical determination (Fig. 3.4) based on results of Shimizu's (1989) theoretical calculations. Shimizu's (1989) estimates of τ_w are preferred as they are based on theoretical reasoning, as opposed to other more empirical methods (e.g., Williams, 1970; Knight, 1981; Flintham and Carling, 1988).

Because the **bankfull** threshold model examines mobility of **bedload** material, the suspended load component must be removed from measured surface and subsurface grain size distributions. To this end a modified version of the approach taken by Kinerson (1990) in examining the q^* theory was employed. The largest suspendable grain size at **bankfull** flow, D_{sus} , was calculated from results of Dietrich's (1982) settling velocity study (Fig. 3.5), assuming a Corey shape factor (CSF) of 0.7 for natural sediments (Dietrich, 1982), $\rho_s = 2650 \text{ kg/m}^3$, $\rho = 1000 \text{ kg/m}^3$, $\nu = 10^{-6} \text{ m}^2/\text{s}$, and $w_s = u^*$, where w_s is the grain fall velocity; in Figure 3.5 w^* and D^* are dimensionless values of grain fall velocity and size. Shear velocities are calculated here from wall-corrected total shear stresses as $u^* = \sqrt{(\tau_0 - \tau_w) / \rho}$. With calculated values of w^* , D^* values were read from Figure 3.5, allowing determination of $D_{sus} = D_n$. Grain sizes less than or equal to D_{sus} were removed from grain size **measurements** and distributions were recalculated. Examination of textural response to other hydraulic roughness elements using grain size distributions corrected in this fashion is, however, paradoxical, as accurate calculation of D_{sus} requires use of τ' and thus knowledge of shear stress dissipation caused by hydraulic roughness features. Because D_{sus} is calculated here using $\tau' = \tau_0 - \tau_w$ (neglecting τ_f , τ_l , and any other sources of shear stress dissipation), D_{sus} values are likely overestimated for all but the plane-bed channels. The resultant magnitude of error in determining D_{50s} and D_{50ss} cannot be predicted as the

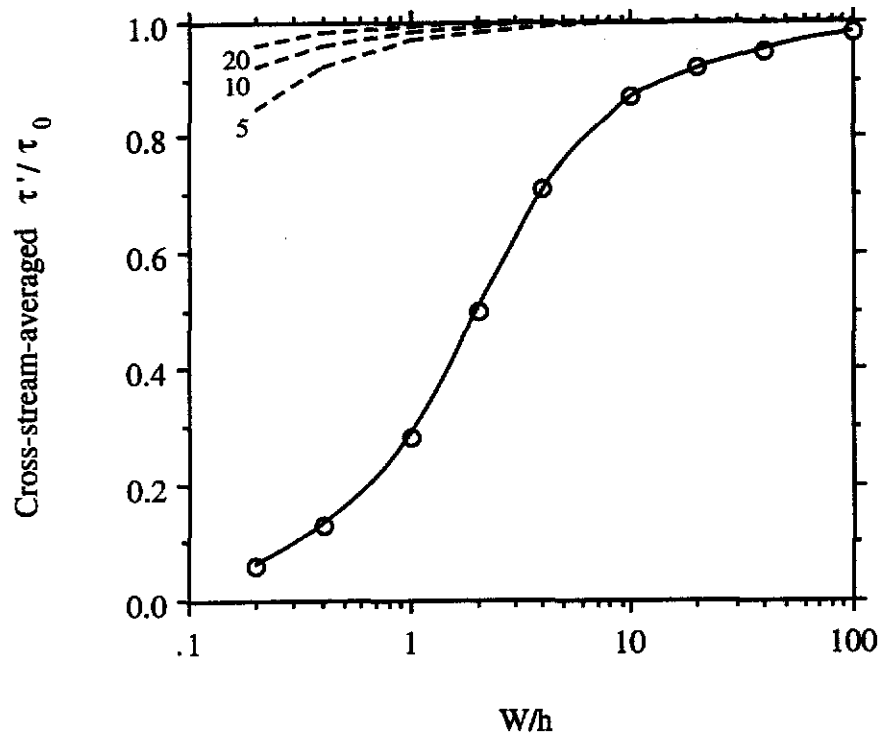


Figure 3.4 Calculated cross-stream-averaged ratio of effective shear stress to total shear stress (i.e., τ'/τ_0) as a function of channel width-to-depth ratio in a straight, unobstructed, rectangular, plane-bed channel. Redrawn from Shimizu's (1989) Figure 8c for uniform bed and wall roughness length scales. Williams' (1970) sidewall correction factor is also shown (dashed lines, **with** numbers indicating channel width) and is seen to be trivial compared to Shimizu's (1989). Williams' (1970) correction factor applies to centerline shear stress (as opposed to cross-sectionally-averaged) and was measured under conditions in which sidewalls were considerably smoother than the bed surface; both of which result in smaller sidewall correction factors [cf. Shimizu's (1989) Fig. 8a-c] that are inappropriate for cross-sectionally-averaged shear stresses of channels with significant wall roughness.

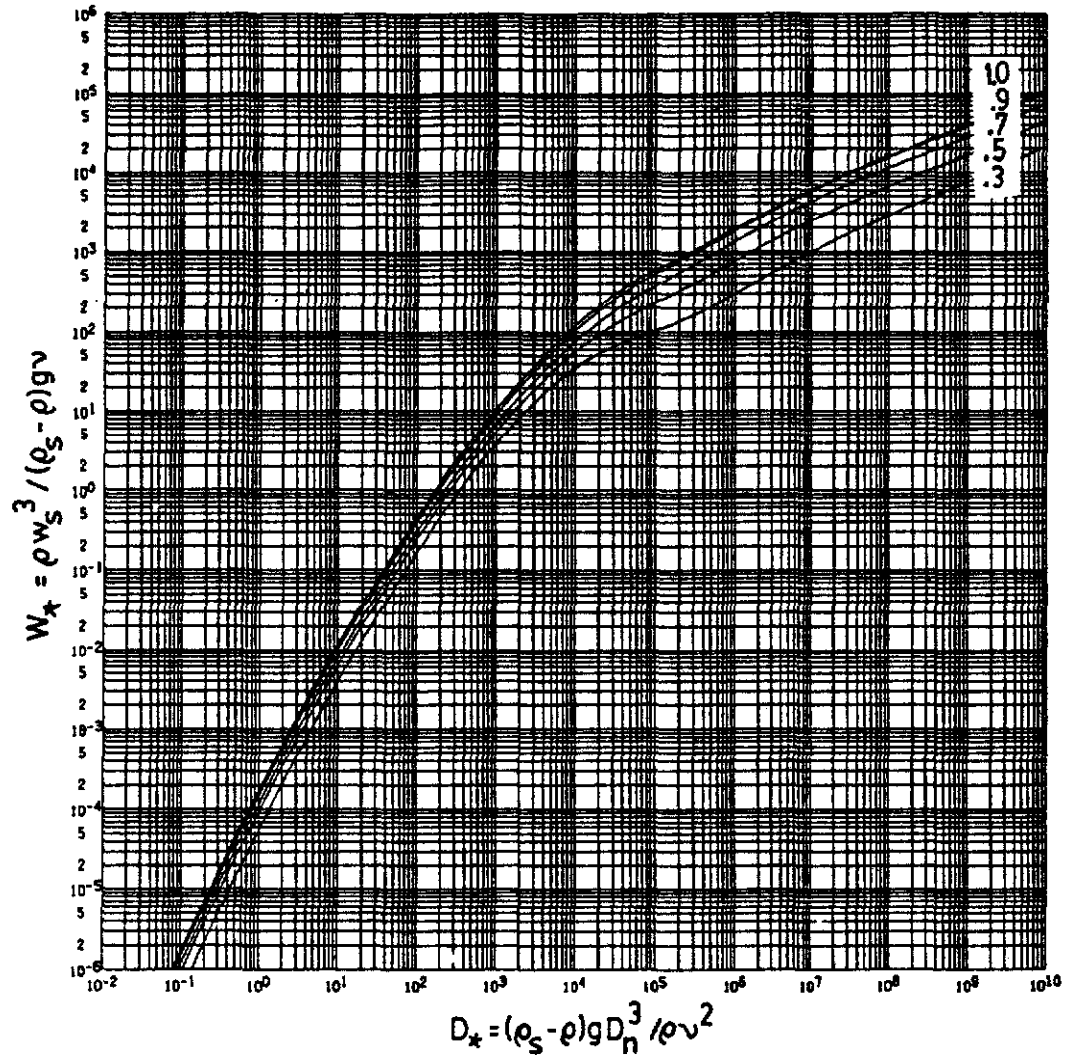


Figure 3.5 Dimensionless grain settling velocity versus dimensionless grain diameter.

Taken from **Dietrich** (1982).

error is dependent on the specific character (i.e., range, skew, and kurtosis) of a given grain size distribution. Nevertheless, potential overestimations of D_{sus} will have a conservative effect on assessment of textural response to sediment supply and hydraulic roughness elements, as overestimated D_{sus} values will **increase D_{50s} and D_{50ss}** , reducing the magnitude of grain size deviation from model **predictions**.

Alaskan Study Sites

A variety of information was collected in the Alaskan field study and is detailed elsewhere (Smith and Buffington, 1990; in press), while the information relevant to the current investigation is briefly reported here. Five cross sections and a center-line bed profile were surveyed with an engineer's level over study reaches that were generally 20 channel widths long. At each cross section a bank-to-bank random pebble count of 100 grains was conducted. Because the Forest Service data were collected for study purposes other than the current investigation there are differences in the way reach-average grain sizes were determined, spatial averaging of mapped **textures** (Olympic) versus averaging discrete cross-channel areas sampled at fixed intervals (Alaskan). It is assumed, however, that the two sampling techniques are comparable. This assumption will be further examined later in the chapter.

Channels were segregated by land use history in the Forest Service study (Smith and Buffington, in press). Here, however, I am more interested in differences in wood loading and subsequent potential influences on surface textures. Although pristine and managed land use types can be discriminated based on wood loading (Smith and Buffington, in press), on the whole the Alaskan channels exhibit a continuum of LWD loading. Figure 3.6 illustrates this continuum and is used to segregate debris-poor from

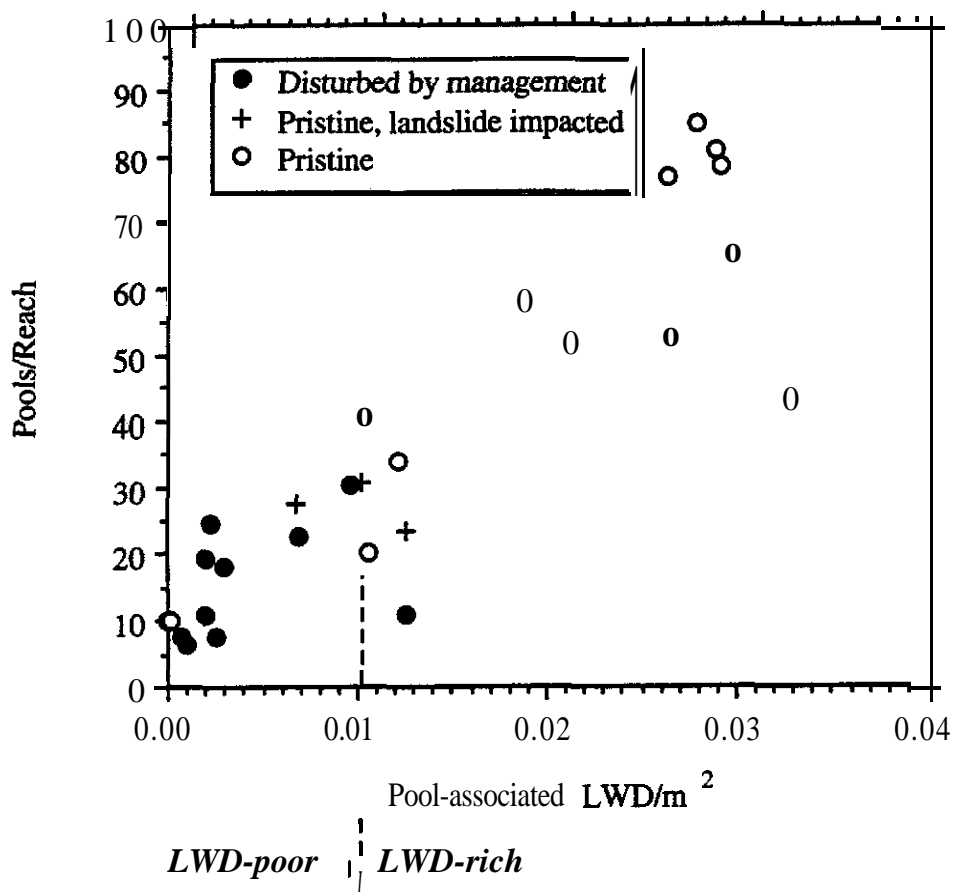


Figure 3.6 Pool frequency (number/reach, where a reach is twenty **bankfull channel** widths long) versus pool-associated LWD loading (pieces/m^{*}) in pristine and managed channels of southeast Alaska. Channels are empirically divided into LWD-poor and **LWD-rich** categories at the median value of pool-associated LWD loading (0.0103 pieces/m^{*}).

debris-rich pool-riffle channels by a simple division of the channels at the median of the LWD loading spectrum (0.0103 pieces/m²). This division correlates well with land use history; further explanation of a similar **figure** and other morphologic distinctions of land use **type** are discussed by Smith and Buffington (in press). The direct correlation of numbers of pools with **LWD** loading seen in Figure 3.6 demonstrates the morphologic significance of **LWD** in forest gravel-bedded streams [see also Montgomery et al. (in press)].

Because all in-channel LWD was inventoried in the Olympic **streams**, while only pool-associated **LWD** was **recorded** in the Forest Service study, it was necessary to derive a conversion factor for the two types of LWD measurement before the data sets could **be** combined. Using data collected during Montgomery and others' (in press) pool spacing study, a reasonably good correlation is observed between pool-associated **LWD/m²** and all in-channel **LWD/m²** (Fig. 3.7); the plotted data are from southeast Alaskan channels, some of which are the same reaches studied by Smith and Buffington (in press) and used in the current analysis. Based on the correlation shown in Figure 3.7 the median value of **pool-associated** wood loading given in Figure 3.6 is equivalent to a total wood loading of about 0.0328 pieces/m²; this value was used to separate the Olympic pool-riffle channels into debris-rich and debris-poor categories, providing a common definition of channel type for the Olympic and Alaskan sites.

RESULTS AND DISCUSSION

*Channel **Geometry** and LWD Loading*

Reach-average **bankfull** geometries for the Olympic and Alaskan study sites are shown in Table 3.3. Overall, the data represent a broad range of slopes (**0.0017-0.0371**), **bankfull** widths (4.0-28.1 m), depths (0.33-1.16 m), width-to-depth ratios (W/h, **7.26-**

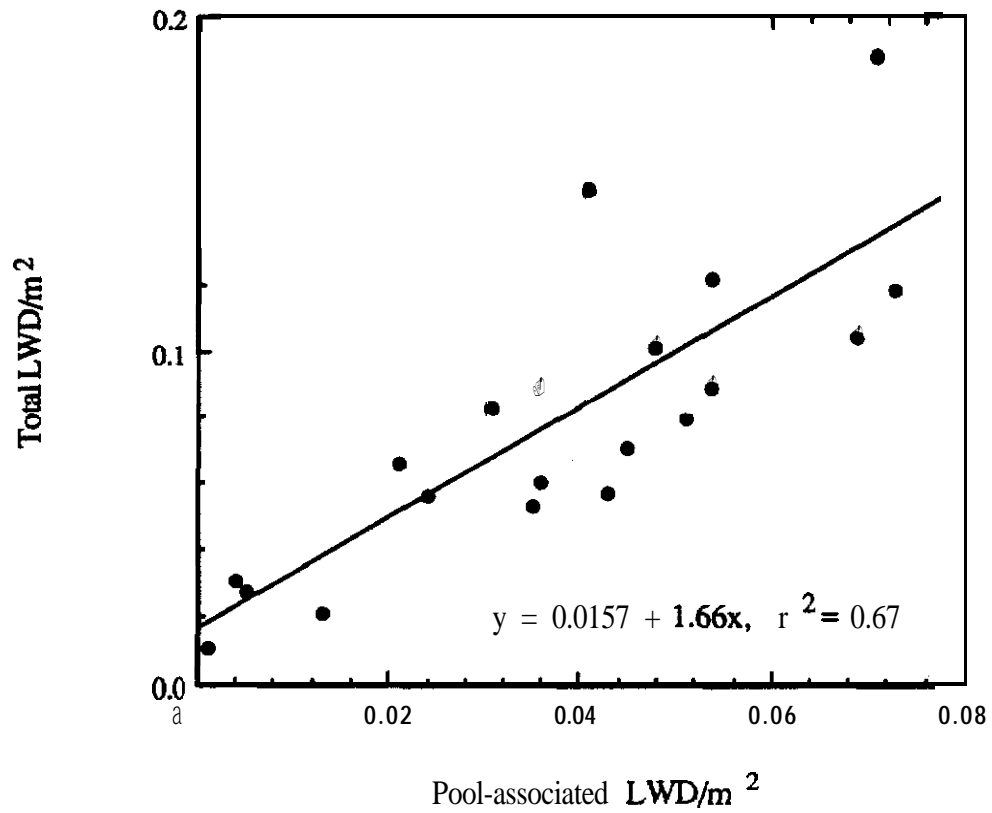


Figure 3.7 Relationship between pool-associated LWD/m^2 and total LWD/m^2 for Alaskan sites studied by Montgomery et al. (in press).

TABLE 3.3: Reach-Average Bankfull Hydraulic Geometry, D_{50b} , and τ_w/τ_0

Channel	Slope	width (m)	Depth (m)	Width/Depth	D_{50b} (mm) [†]	τ_w/τ_0
Olympic Channels						
<i>Plane-bed</i>						
Upper Dry Creek	0.0122	6.84	0.59	11.59	67.1 (68.7)	0.122
Alder Creek*	0.0257	a. 37	0.62	13.50	56.4 (61.0)	0.113
Hoko Tributary	0.0160	5.02	0.35	14.34	54.8 (55.2)	0.108
Lower Hoh Slough	0.0059	11.53	0.51	22.61	19.3 (41.8)	0.072
Upper Hoh Slough	0.0114	10.65	0.56	19.02	56.8 (61.2)	0.085
<i>LWD-poor Pool-riffle</i>						
Upper Skunk Creek	0.0126	7.02	0.97	7.24	39.2 (44.2)	0.204
Hoko River	0.0085	13.41	0.81	16.56	35.0 (36.9)	0.097
Lower Pins Creek	0.0071	6.39	0.48	13.31	31.4 (33.0)	0.113
<i>LWD-rich Pool-riffle</i>						
Upper Pins Creek	0.0133	6.17	0.50	12.34	36.0 (39.3)	0.118
Flu Hardy Creek	0.0105	6.83	0.62	11.02	24.4 (29.2)	0.125
Mill Creek	0.0143	8.72	0.88	9.91	19.4 (24.0)	0.132
Lower Dry Creek*	0.0222	7.90	0.59	13.39	53.4 (55.9)	0.113
Lower Skunk Creek	0.0040	13.36	0.80	16.70	19.8 (23.8)	0.097
Cedar Creek	0.0046	11.51	0.62	18.56	27.2[‡]	0.087
Southeast Alaskan Channels						
<i>LWD-poor Pool-riffle</i>						
12 Mile Creek 1	0.0021	23.34	0.95	24.57	24.1[‡]	0.073
12 Mile Creek 2	0.0028	23.35	1.09	21.42	21.7 (24.9)	0.078
Maybeso Creek I	0.007 1	22.3 1	1.13	19.74	49.4 (53.3)	0.081
Maybeso Creek 2	0.0065	28.10	0.84	33.45	36.1 (38.0)	0.060
Maybeso Creek 3 [£]	0.0023	26.95	0.93	28.98	36.2[‡]	0.067
Maybeso Creek 4 [£]	0.0036	24.48	1.06	23.09	46.2 (47.7)	0.075
Cable Creek	0.0017	16.89	0.88	19.19	13.1[‡]	0.084
Fubar Creek 1	0.0106	17.64	0.62	28.45	42.9 (47.4)	0.055
Fubar Creek 2	0.0127	16.32	0.79	20.66	56.8 (60.8)	0.079
Indian Creek [£]	0.0121	24.37	1.16	21.01	79.3 (82.9)	0.078
Muri Creek [£]	0.0149	14.29	0.59	24.22	44.1 (53.5)	0.074
Bambi Creek	0.0091	4.0	0.33	12.12	17.4 (18.8)	0.119
Upper Weasel creek 2*	0.0023	15.10	0.92	16.41	25.4[‡]	0.098
Lower Greens Creek'	0.0371	12.90	0.66	19.55	47.0 (53.6)	0.082
<i>LWD-rich Pool-riffle</i>						
Hook Creek'	0.0109	17.33	0.76	22.80	27.2 (32.2)	0.076
Trap Creek 1	0.0055	12.63	0.86	14.69	16.7 (17.8)	0.107
Trap Creek 2	0.0067	15.29	0.62	24.66	15.1 (15.8)	0.073
Trap Creek 3	0.0077	11.78	0.58	20.30	14.8 (17.2)	0.079
Trap Creek 4	0.0071	9.54	0.69	13.83	11.6 (16.2)	0.111
Trap Creek 5	0.0101	13.73	0.66	20.80	15.9 (20.3)	0.079
Trap Creek 6	0.0120	14.60	0.65	22.46	13.4 (18.7)	0.073
East Fork Trap Creek 1	0.0126	14.61	0.59	24.76	14.5 (23.5)	0.066
East Fork Trap Creek 2	0.0125	11.20	0.55	20.36	24.2 (27.4)	0.079
Fowler Creek 1	0.0062	18.39	0.67	27.45	13.9 (18.5)	0.058
Fowler Creek 2	0.0055	12.20	0.65	18.77	18.9 (24.5)	0.086
Lower Fish Creek	0.0270	19.03	1.02	18.66	25.7 (32.3)	0.087
Upper Fish Creek	0.0224	12.88	0.56	23.00	45.6 (48.5)	0.076

[†] Values in parentheses are derived from grain size distributions truncated at D_{50b} and are thus indicative of bedload material only.

[‡] Bedload and suspended load material could not be differentiated as the calculated D_{50b} value is < 2 mm, the minimum resolution used for surface pebble counts; all grain sizes ≤ 2 mm were lumped into one category and are consequently undifferentiable.

* Evidence of catastrophic sediment inputs.

[£] Transitional between pool-riffle and plane-bed morphology.

33.49, and median surface grain sizes (10.6-79.3 mm). The Alaskan **channels** typically have larger **W/h**, with **the** debris-poor channels having higher ratios on average than the debris-rich channels; greater W/h ratios are attributed to larger drainage areas for the debris-poor channels compared to those of the debris-rich (Smith and Buffington, in press). The ratio of τ_w to τ_0 for each channel is also given in Table 3.3, with values ranging from **0.055-0.204**.

Composite distributions of LWD loading (**pieces/m²**) for the **three** channel types studied are presented in Figure 3.8. Debris loading for the Alaskan sites was calculated from the relation given in Figure 3.7. The plane-bed channels are virtually debris-free, while the pool-riffle channels have variable loading (Fig. 3.8). By definition the **debris-poor** channels have loadings less than 0.0328 **pieces/m²**. The bulk of the debris-poor channels have a small, narrow range of loadings (0.0158-0.0323 pieces/m²) with a median of 0.0200 pieces/m². In contrast, the majority of the LWD-rich channels have a much broader and higher range (0.0339-0.0688 pieces/m²), with a median value nearly **three** times greater than the pool-riffle channels classified as debris-poor.

Surface Textures of the Olympic Channels

Mapped surface textures of the Olympic channels are **summarized** in Table 3.4 by channel type. Examples of topographic, textural, and LWD maps for each channel type are also provided (Maps 1-5); because the pool-riffle channel types are quite variable, two maps of each of these types are presented. Numbers of textures observed in a reach varied from one to seven and were composed of grain sizes ranging from silt to small boulders. No formal grain size analysis was done for textural patches formed completely of either sand or silt, instead an approximate median grain size was assigned (2 or 0.0625 mm, respectively). Cumulative grain size distributions of sampled textures **are** shown in Figure 3.9, Except for T4 of Upper Hoh Slough, pebble counts of visually identical textures

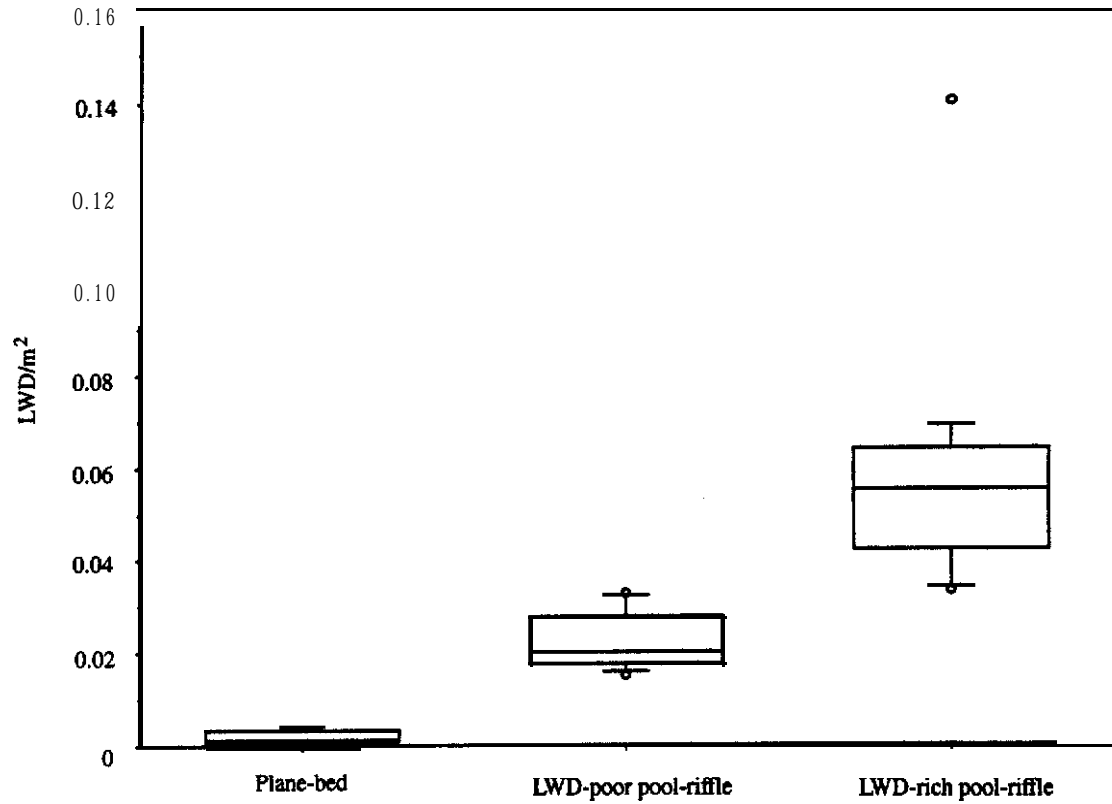


Figure 3.8 Composite LWD loading (pieces/m²) distributions for **the three** channel types studied. **Line within** each box plot represents the median value of the distribution, box ends **are** the inner and outer quartiles, whiskers are the inner and **outer** tenths, and circles are extrema.

TABLE 3.4: Surface Textural Composition of the Olympic Channels

Channel	Reach D_{50s} (mm) [†]	Texture	% of Bed	Patch Frequency (#/reach) [‡]	D_{50s} (mm) [†]	$ \sigma_{gs} (\phi)$ [†]
<i>Plane-bed</i>						
Upper Dry Creek	67.1 (68.7)	T1: cobble, gravel	100	1	67.1 (68.7)	1.24 (1.19)
Alder Creek	56.4 (61.0)	T1: cobble, boulder, gravel	100	1	56.4 (61.0)	1.58 (1.28)
Hoko Tributary	54.8 (55.2)	T1: cobble, gravel	100	1	54.8 (55.2)	1.34 (1.31)
Lower Hoh Slough	19.3 (41.8)	T1: sand, gravel	63	3	9.0 (42.7)	2.76 (1.26)
		T2: gravel, cobble	35	3	38.9 (40.3)	1.10 (1.05)
		T3: sand	2	2	-2.0 (na)	
Upper Hoh Slough	56.8 (61.2)	T1: sand, gravel	4	1	9.0 (42.7)	2.76 (1.26)
		T2: gravel, cobble	0.5	1	38.9 (40.3)	1.10 (1.05)
		T3: sand	4	2	-2.0 (na)	
		T4: cobble, gravel, boulder	91.5	1	61.4 (63.6)	1.54 (1.48)
<i>LWD-poor Posh-riffle</i>						
Upper Skunk Creek	39.2 (44.2)	T1: cobble, gravel	71.24	2	50.4 (51.1)	1.10 (1.07)
		T2: gravel	8.22	4	25.0 (27.8)	1.37 (0.98)
		T3: fine gravel, coarse gravel, cobble	11.19	9	9.9 (12.8)	1.41 (1.06)
		T4: sand	9.33	9	-2.0 (na)	
Hoko River	35.0 (36.9)	T1: gravel, cobble	61.58	4	38.4 (38.8)	1.24 (1.22)
		T2: fine gravel	5.10	7	-6.0 (?)	
		T3: gravel	13.87	9	13.1 (13.5)	0.98 (0.91)
		T4: cobble, gravel	19.45	3	47.4 (47.7)	0.92 (0.92)
Lower Pins Creek	31.4 (33.0)	T1: medium/coarse gravel	2.58	3	12.7 (13.3)	1.15 (1.10)
		T2: gravel, cobble	92.11	1	33.3 (34.6)	1.57 (1.37)
		T3: fine & medium gravel	4.15	6	9.2 (9.8)	1.32 (1.19)
		T4: sand	1.16	3	-2.0 (na)	

[†] Values in parentheses are derived from grain size distributions truncated at D_{sus} and are thus indicative of bedload material only. D_{sus} values for each channel are shown in Figure 3.7. Textures with assigned/estimated D_{50s} values (i.e., T3 and T4 of Flu Hardy, etc.) less than D_{sus} are completely suspendable at bankfull and are given a bedload D_{50s} designation of 'na'; for such cases, reach-average D_{50s} values of bedload material were calculated from re-proportioned areal extents of the remaining textural patches.

[‡] Reach length is ten channel widths.

[‡] Bedload and suspended load material could not be differentiated as the calculated D_{sus} value is < 2 mm, the minimum resolution used for surface pebble counts; all grain sizes ≤ 2 mm were lumped into one category and are consequently undifferentiable.

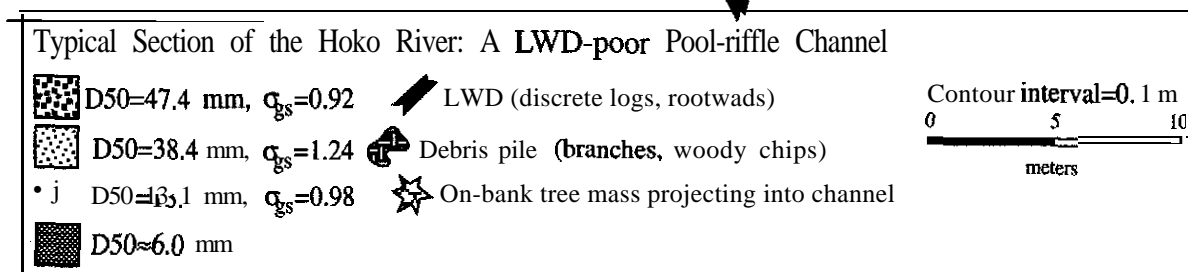
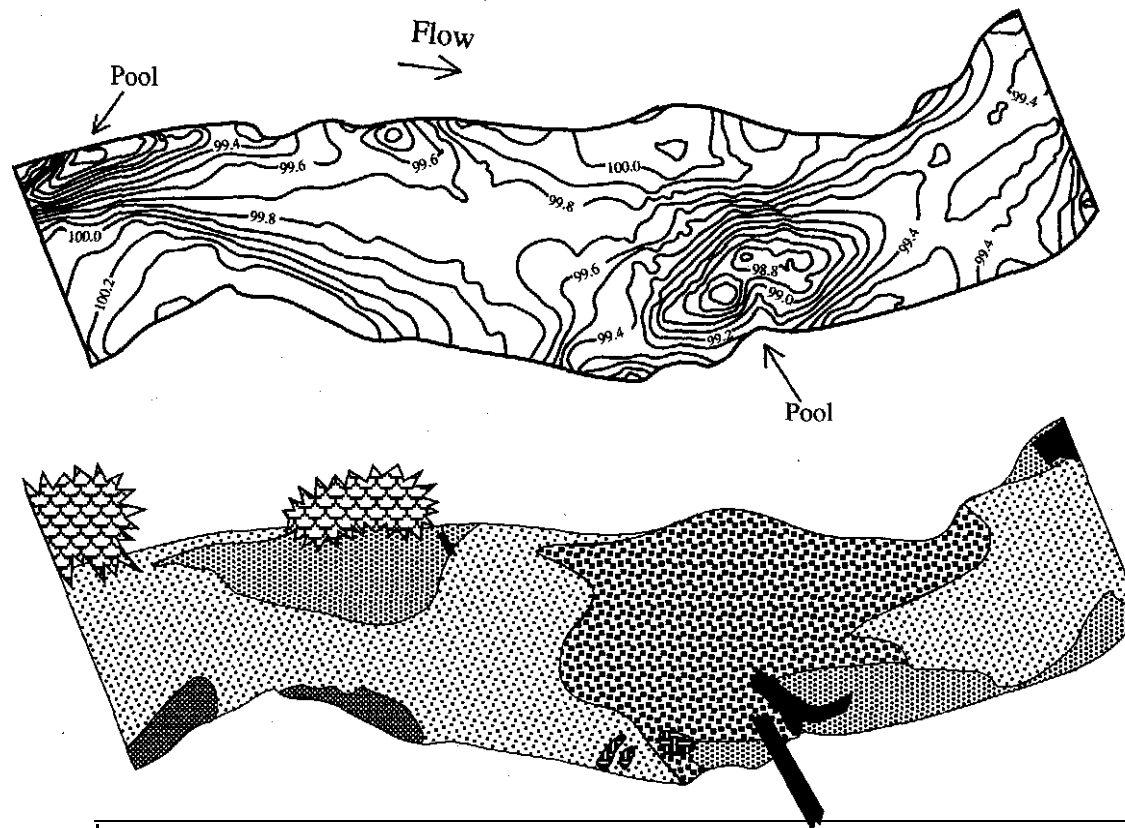
TABLE 3.4 cont

Channel	Reach D_{50s} (mm) [†]	Texture	% of Bed	Patch Frequency (#/reach)	D_{50s} (mm) [†]	$ \sigma_{gs} (\phi)$ [‡]
<i>LWD-rich Pool-riffle</i> upper Pins Creek	36.0 (39.3)	T1: gravel, cobble	40.61	7	52.4 (52.8)	1.01 (1.00)
		T2: coarse gravel	48.47	3	29.6 (30.0)	0.93 (0.91)
		T3: fine gravel	3.22	3	7.1 (8.0)	0.92 (0.52)
		T4: sand	7.71	4	-2.0 (na)	
Flu Hardy Creek	24.4 (29.2)	T1: coarse/medium gravel	80.53	1	29.5 (30.0)	0.89 (0.88)
		T2: medium/line gravel	3.70	6	11.7 (12.0)	0.92 (0.90)
		T3: sand	11.79	9	-2.0 (na)	
		T4: silt	3.98	2	-0.06 (na)	
Mill Creek	19.4 (24.0)	T1: coarse gravel, cobble	8.15	5	39.6 (39.6)	0.58 (0.58)
		T2: medium/coarse gravel	62.57	2	23.7 (24.5)	1.04 (0.94)
		T3: fine gravel	11.77	25	8.4 (10.4)	0.93 (0.68)
		T4: sand	15.89	21	-2.0 (na)	
		T5: silt	1.63	2	-0.06 (na)	
Lower Dry Creek	52.4 (55.9)	T1: cobble, gravel	47.48	8	77.0 (77.4)	0.66 (0.66)
		T2: gravel, cobble	39.28	3	39.1 (39.6)	1.12 (1.09)
		T3: gravel	7.52	5	13.8 (15.7)	1.09 (0.87)
		T4: line gravel, cobble	4.79	2	9.3 (38.8)	2.34 (1.85)
		T5: sand	0.94	3	-2.0 (na)	
Lower Skunk Creek	19.8 (23.8)	T1: gravel, cobble	21.54	4	29.2 (29.2)	0.91 (0.91)
		T2: gravel	62.31	6	21.2 (22.0)	0.96 (0.84)
		T3: sand	16.15	32	-2.0 (na)	
Cedar Creek [‡]	27.2	T1: cobble, gravel	7.53	3	74.4	0.89
		T2: medium gravel, cobble	64.19	1	26.6	0.70
		T3: coarse gravel, cobble	6.15	1	35.3	0.82
		T4: gravel	12.80	11	17.6	0.65
		T5: sand	2.64	3	-2.0	
		T6: tine gravel	1.08	6	6.6	0.98
		T7: silt	5.61	2	-0.06	

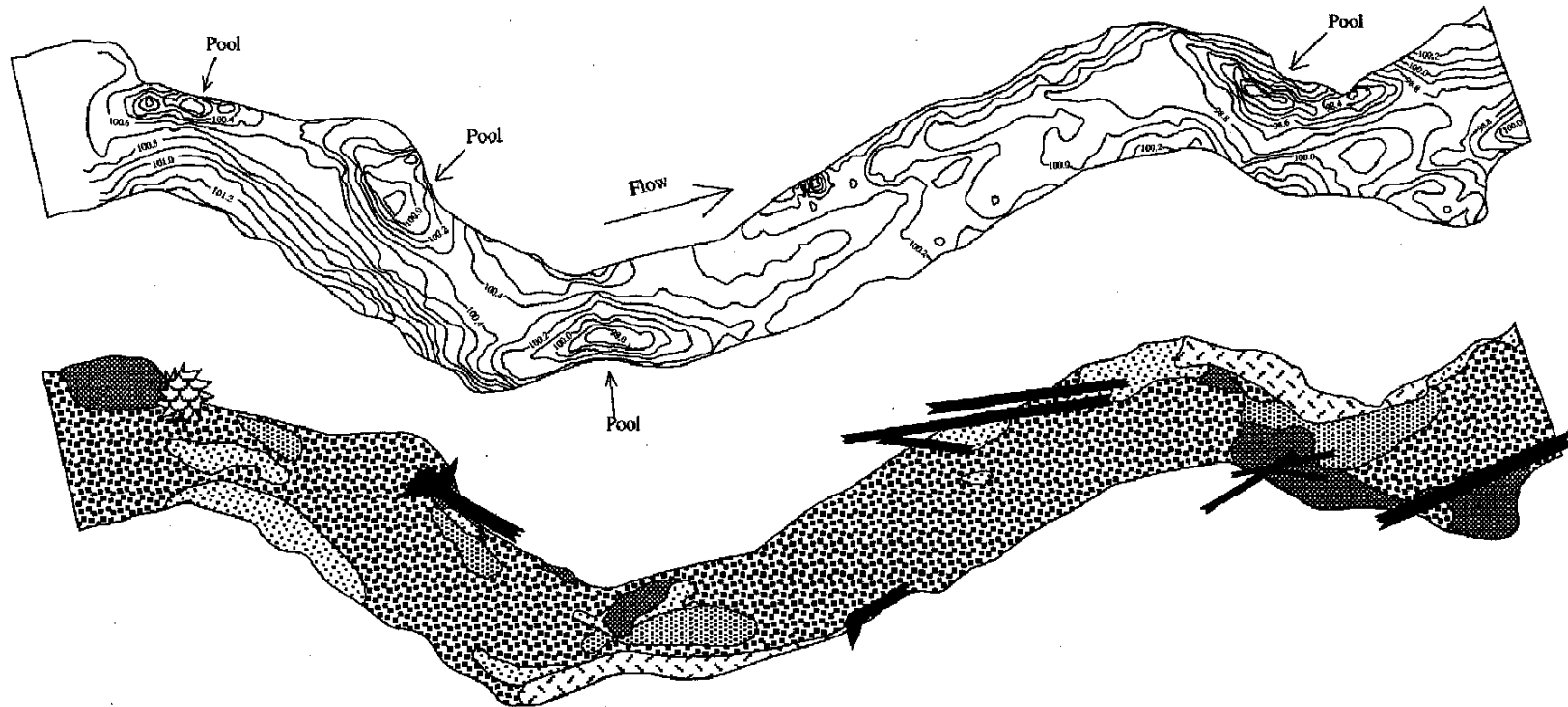
[†] Values in parentheses are derived from grain size distributions truncated at D_{sus} and are thus indicative of bedload material only. D_{sus} values for each channel are shown in Figure 3.7. Textures with assigned/estimated D_{50s} values (i.e., T3 and T4 of Flu Hardy, etc.) less than D_{sus} are completely suspendable at bankfull and are given a bedload D_{50s} designation of 'na'; for such cases, reach-average D_{50s} values of bedload material were calculated from re-proportioned areal extents of the remaining textural patches.

[‡] Reach length is ten channel widths.

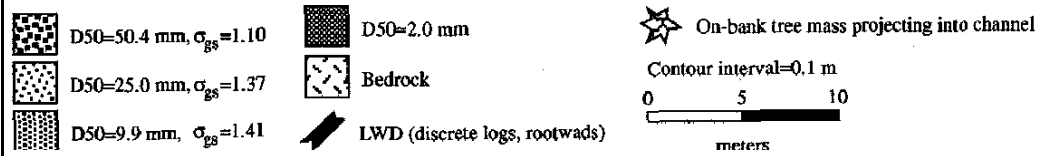
[‡] Bedload and suspended load material could not be differentiated as the calculated D_{sus} value is < 2 mm, the minimum resolution used for surface pebhk counts; all grain sizes ≤ 2 mm were lumped into one category and are consequently undifferentiable.



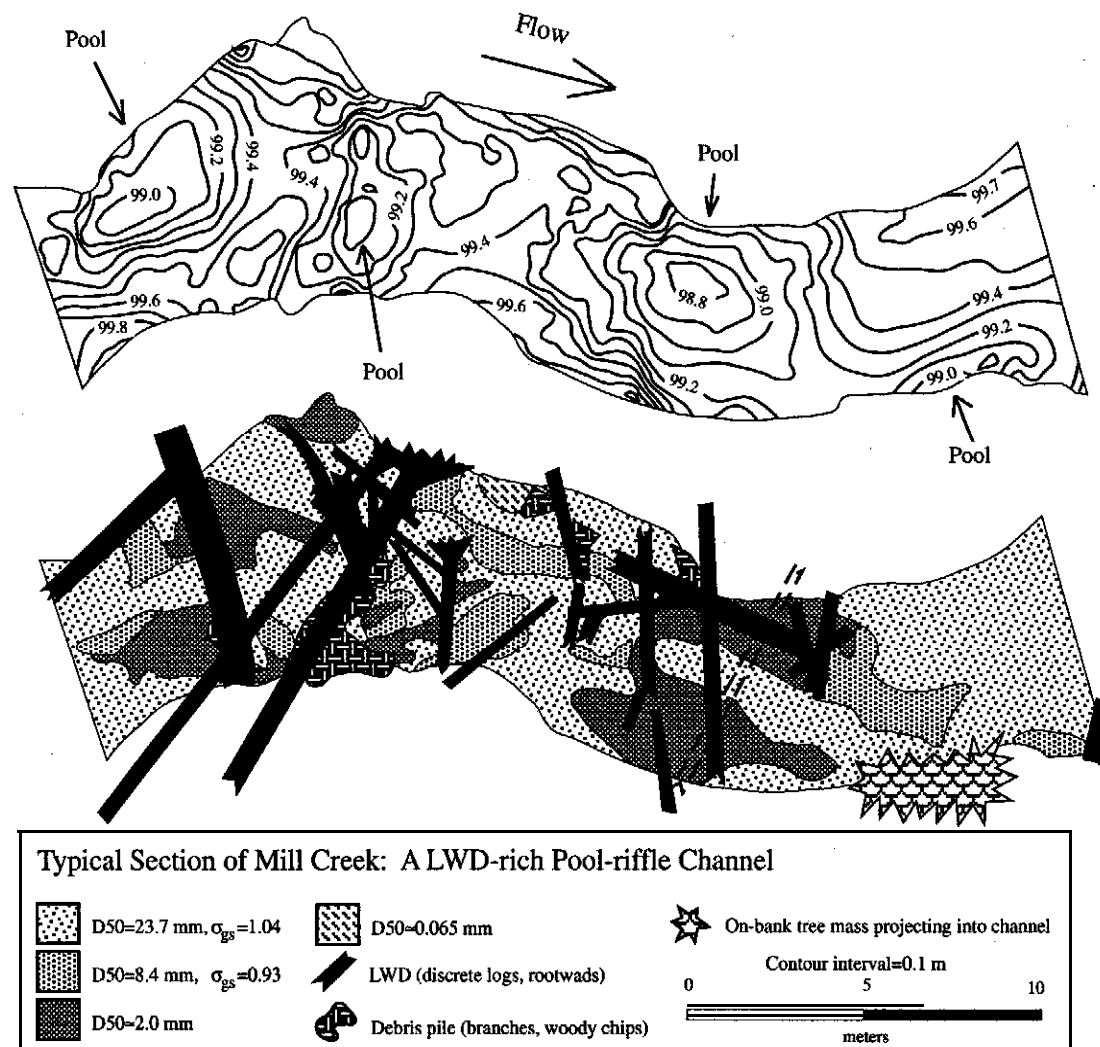
Map 2: Typical section of the Hoko River, a **LWD-poor** pool-riffle channel. Section shown is three channel widths long.



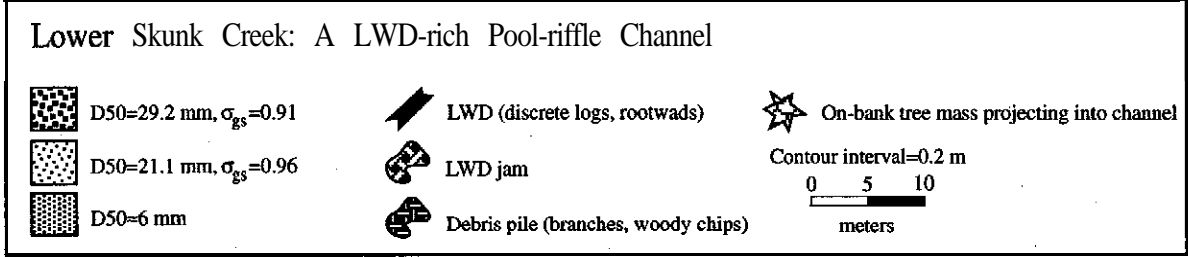
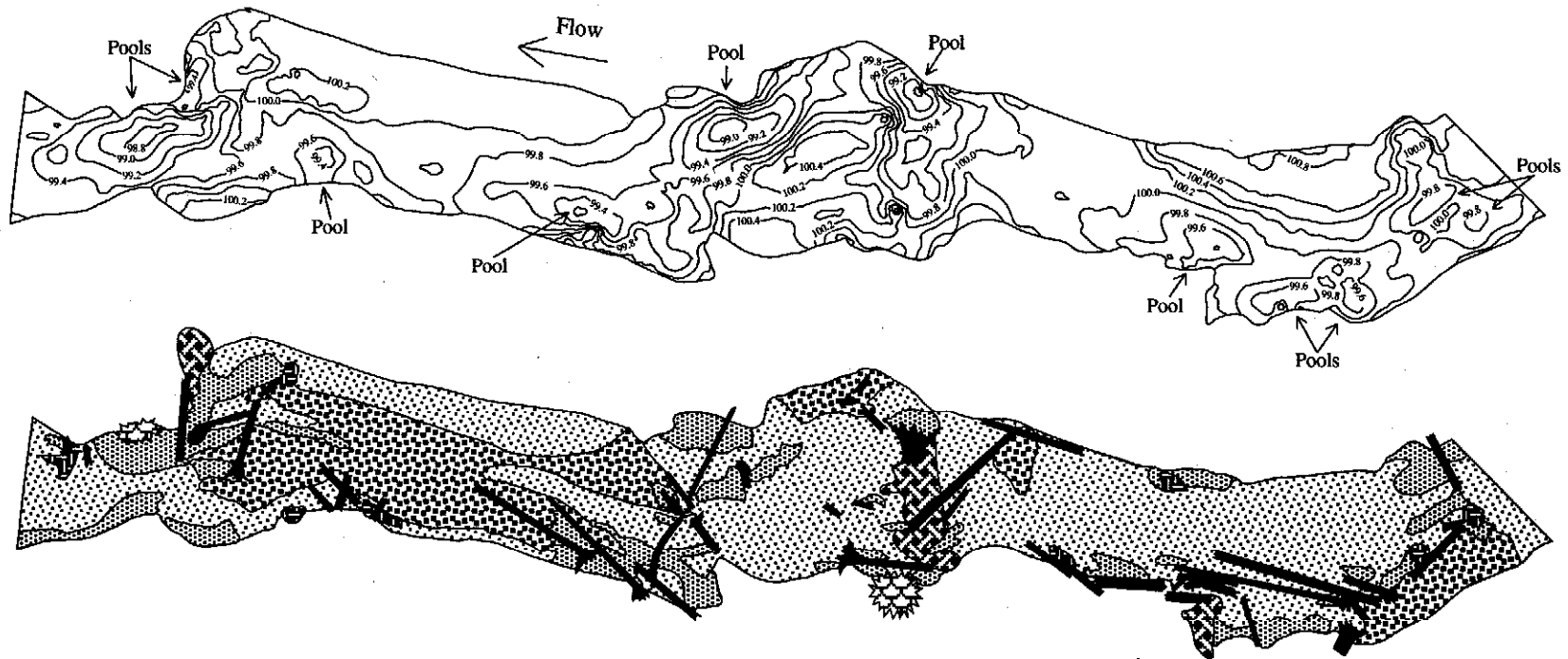
Upper Skunk Creek: A **LWD-poor** Pool-riffle Channel



Map 3: Upper Skunk Creek, a **LWD-poor** pool-riffle channel. Reach shown is ten channel widths long



Map 4: Typical section of Mill Creek, a **LWD-rich** pool-riffle channel. Section shown is 3.4 channel widths long.



Map 5: Lower Skunk Creek, a LWD-rich pool-riffle channel. Reach shown is ten channel widths long.

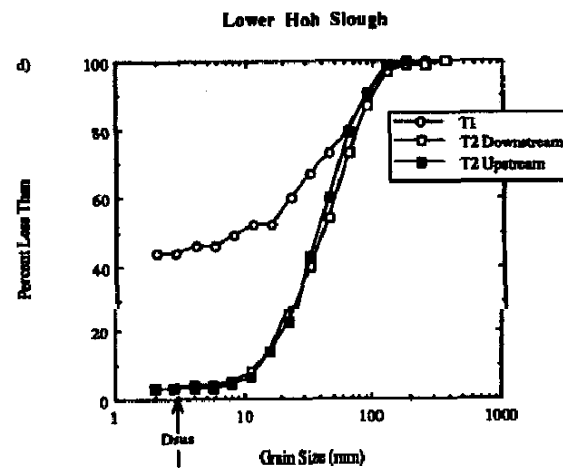
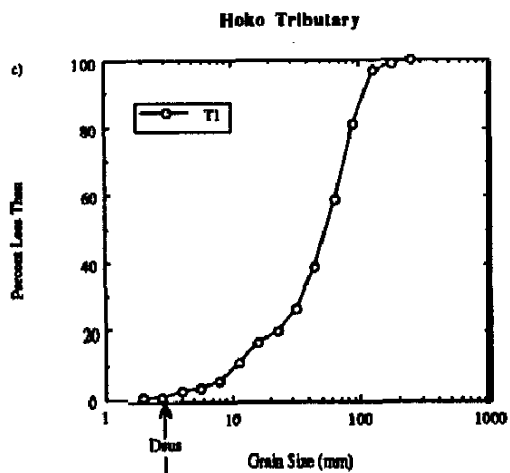
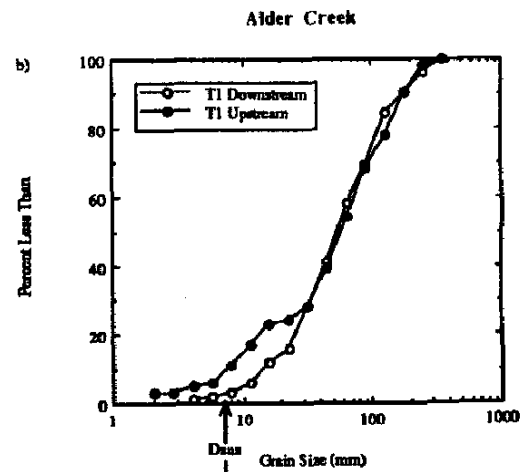
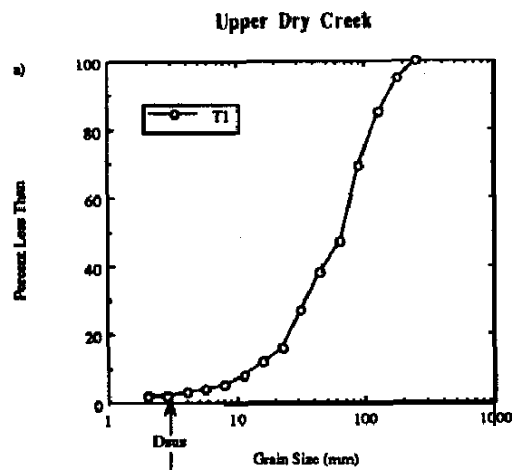


Figure 3.9 Surface, in size distributions of textures pped the Olympic study sites, Abscissa arrow indicates calculated reach-average D_{sus} lue.

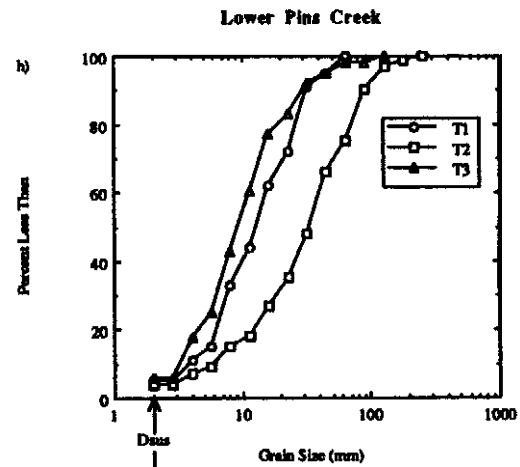
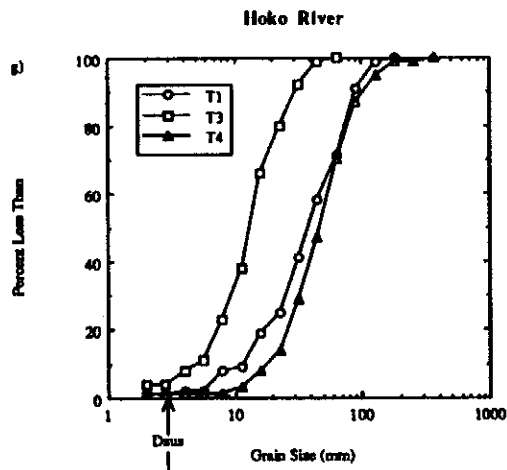
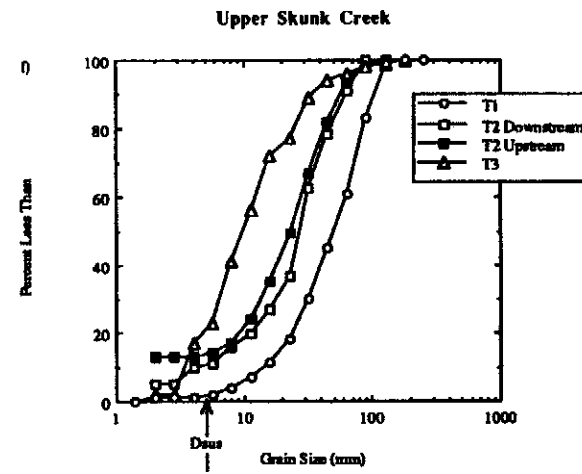
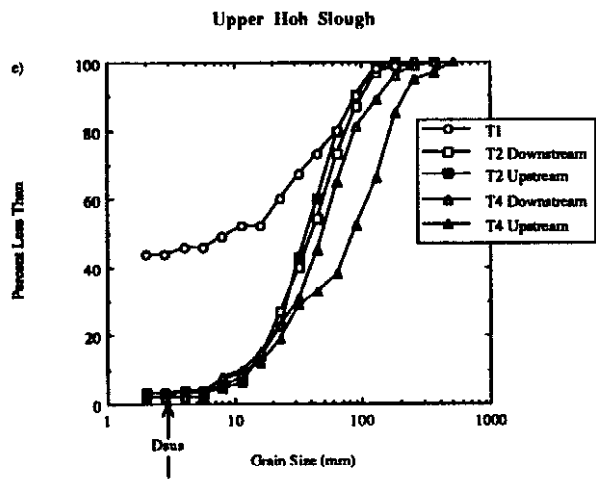


Figure 3.9 cont.

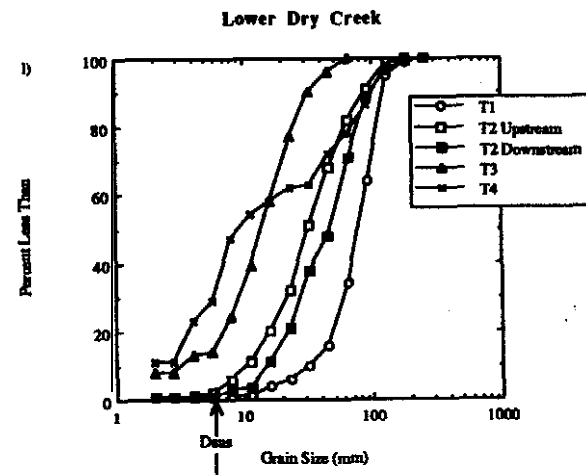
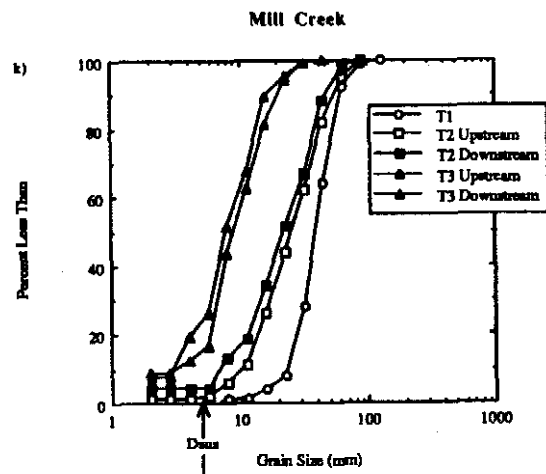
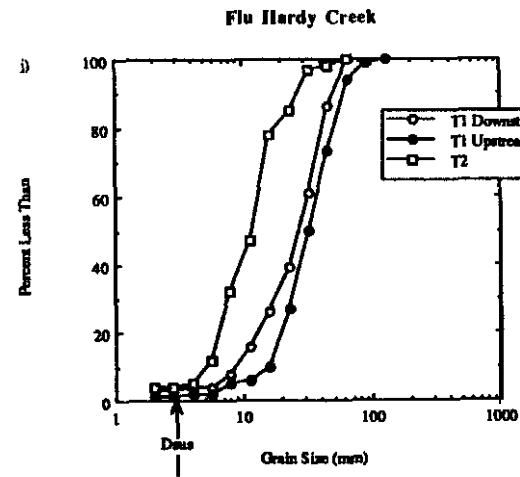
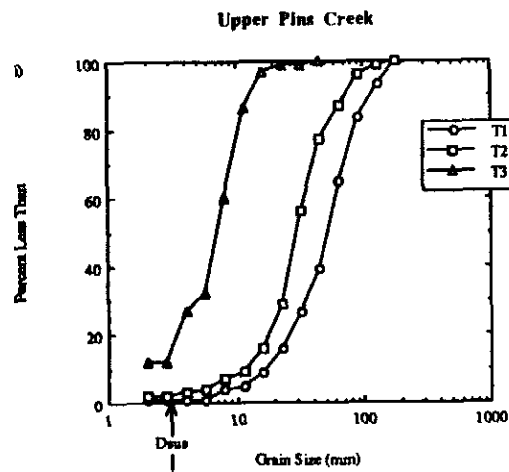


Figure 3.9 cont.

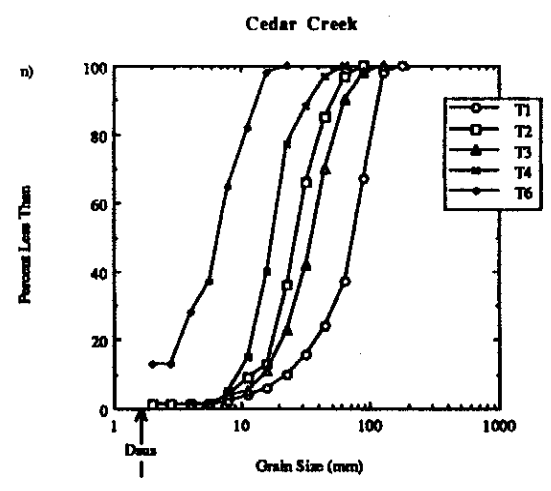
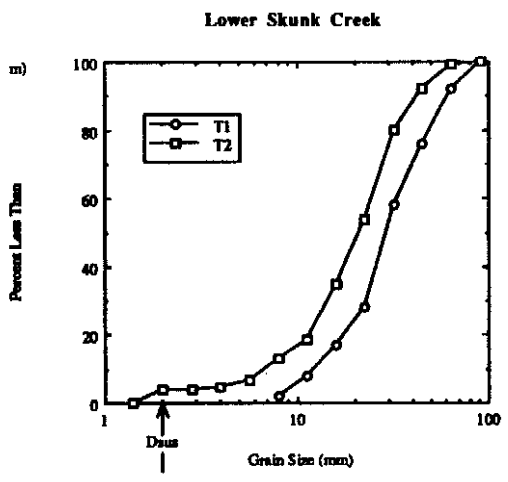


Figure 3.9 cont.

located in different portions of a reach yield similar grain **size distributions** (Fig. 3.9b, d, f, j, k, l), generally validating the procedure of **characterizing** textures by sampling a single patch. In contrast, some facies identified in the field as **visually** distinctive show fairly similar grain **size** distributions [e.g., Fig. 3.9g (T1,T4)]; however, differences in sorting coefficients lend credence to the field partitioning of these **textures** as different from one another (Table 3.4). Partitioning similar textures as different does not significantly affect reach-average evaluations of **D_{50s}**. While facies mapping accurately **characterizes** spatial distributions of textures, the reach-average **D_{50s}** values reported here should be viewed as **first-order** estimates (as opposed to **zero-order**) due to the small number of textural patches sampled per reach.

Facies mapping demonstrates that the number and spatial distribution of surface textures is strongly influenced by channel type. Plane-bed channels exhibit one to four grain-size facies, but are typically mono-textural (Table 3.4). Each of the LWD-poor **pool-riffle channels** are composed of four textures, while LWD-rich pool-riffle channels exhibit three to seven facies per reach. Thus, the number of textures increases with greater complexity of channel roughness. Furthermore, complexity of the spatial distribution of textures **increases** with complexity of channel roughness (Maps 1-5). The total frequency of textural patches within a reach ranges from **1-8** in plane-bed channels, but increases to 13-24 in LWD-poor pool-riffle channels and 17-55 in LWD-rich pool-riffle streams (Table 3.4). The data also show a slight increase in sorting (i.e., lower **σ_{gs}** values) with increasing channel roughness (Table 3.4); bedload-material surface textures in plane-bed channels are **poorly** sorted, while LWD-rich pool-riffle streams tend to have moderately **sorted** textures.

An **increase** in textural complexity from plane-bed to pool-riffle channels is not surprising, given previous observations of textural variation in sinuous pool-riffle channels. Systematic downstream and cross-channel variation in shear stress can be

caused by channel curvature and topographically-induced convective accelerations (Dietrich and Smith, 1983; **1984a; 1984b; Dietrich** et al., 1979). In a meander bend it is commonly observed that surface grains fine both downstream along the point bar and cross-stream from the pool to the bar. These textural variations reflect the shifting of the high velocity core across the bar toward the pool, causing flow convergence in the pool and divergence along the bar (Dietrich and Smith, 1983; **1984a; 1984b; Dietrich** et al., 1979). Mechanics of topographically-induced shear stress and textural variation are essentially similar in both sinuous and straight channels (Nelson and Smith, **1989a**). Predictable textural variations of this sort occur in some of the **pool-riffle** sequences of the Olympic channels, but **are** by no means ubiquitous and tend to be less common in the LWD-rich streams (Maps 2-5). In-channel obstructions complicate flow patterns and modify local shear stresses, causing spatially complex textural arrangements that are not as readily predictable as in **obstruction-free** pool-riffle channels. Differences in textural patch frequency and the **finer** scale of textural partitioning noted above result from a progressively greater frequency of LWD obstructions in the sequence of channel types examined (Fig. 3.10). **Patch** frequency is a power function of LWD loading.

Despite the observed complexity of textural sequences, some general patterns of channel unit textural composition can **be identified** from the field maps; channel units are basic morphologic components of a stream reach (i.e., pools, bars, etc.) (**Bisson** et al., 1982; Sullivan, 1986; Grant et al., 1990; Church, 1992; Smith and **Buffington**, in press). Figure 3.11 shows the relative **areal** extent of facies within pool, bar, and riffle channel units; surface textures are divided here into reach-specific, relative categories of coarse, intermediate and **fine** grain sizes. Of the facies present in each channel, coarse and intermediate textures comprise the majority of bar-forming grains in both debris-rich and debris-poor streams (Fig. 3.11). Fine textures are almost always present on bar surfaces, but usually in relatively small quantities. **In** contrast to similar bar-form textural

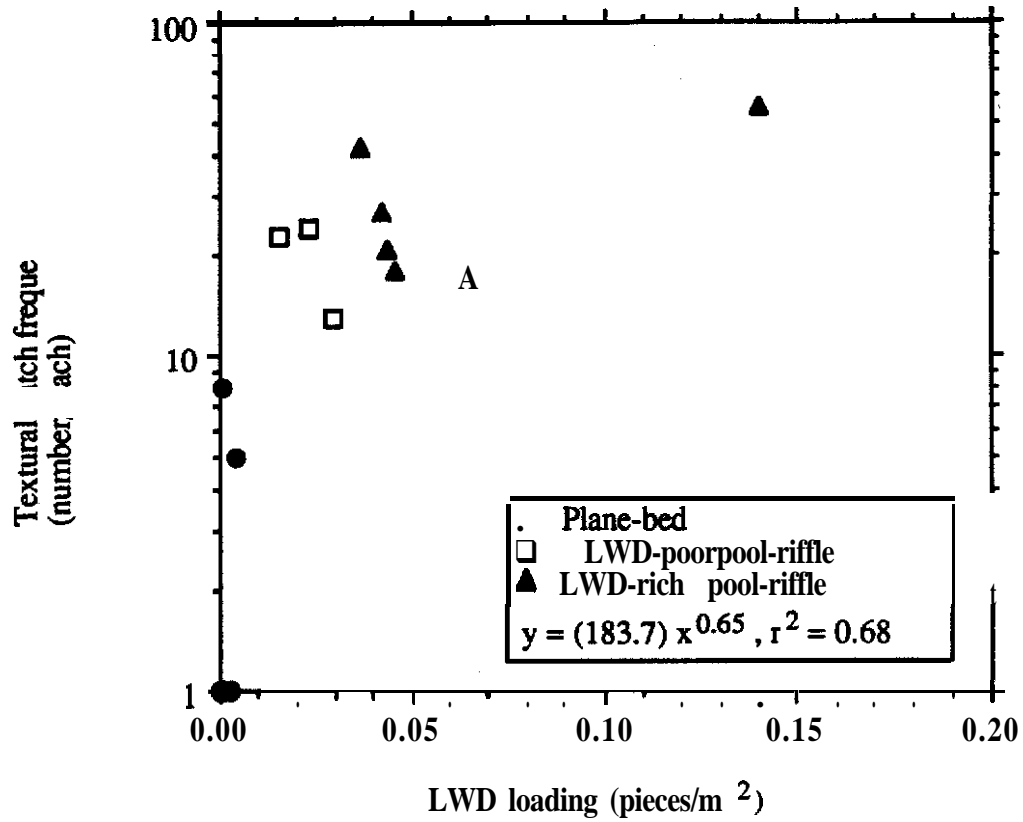


Figure 3.10 Textural patch frequency (number/reach) versus LWD loading (pieces/m²) stratified by channel type.

LWD-poor Pool-riffle Channels

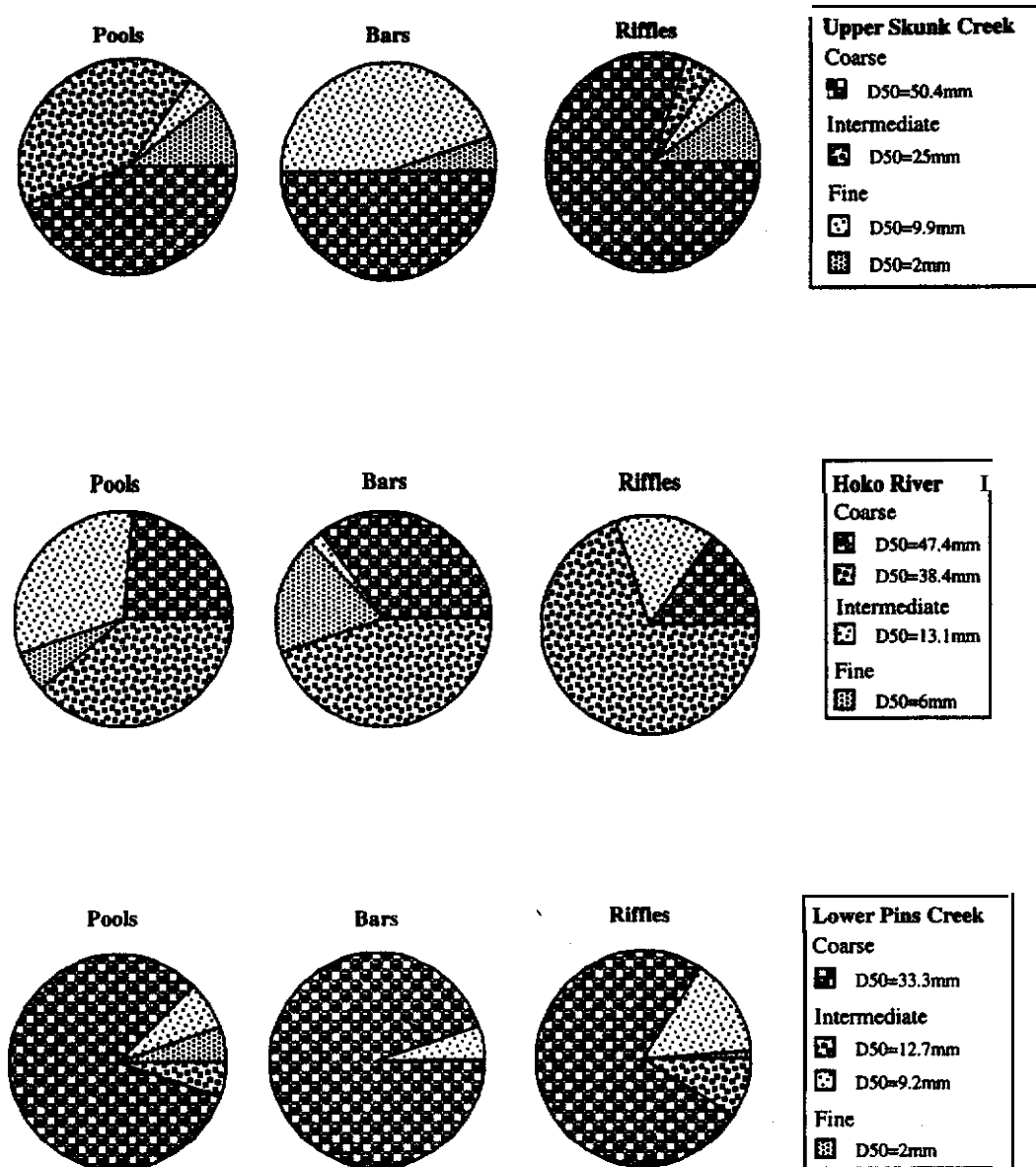


Figure 3.11 Textural composition of pool, bar, and riffle channel units expressed as relative **areal** extents. Grain size divisions of coarse, intermediate, and fine are based on reach-specific relative sizes observed in the field and quantified by Figure 3.9.

LWD-rich Pool-riffle Channels

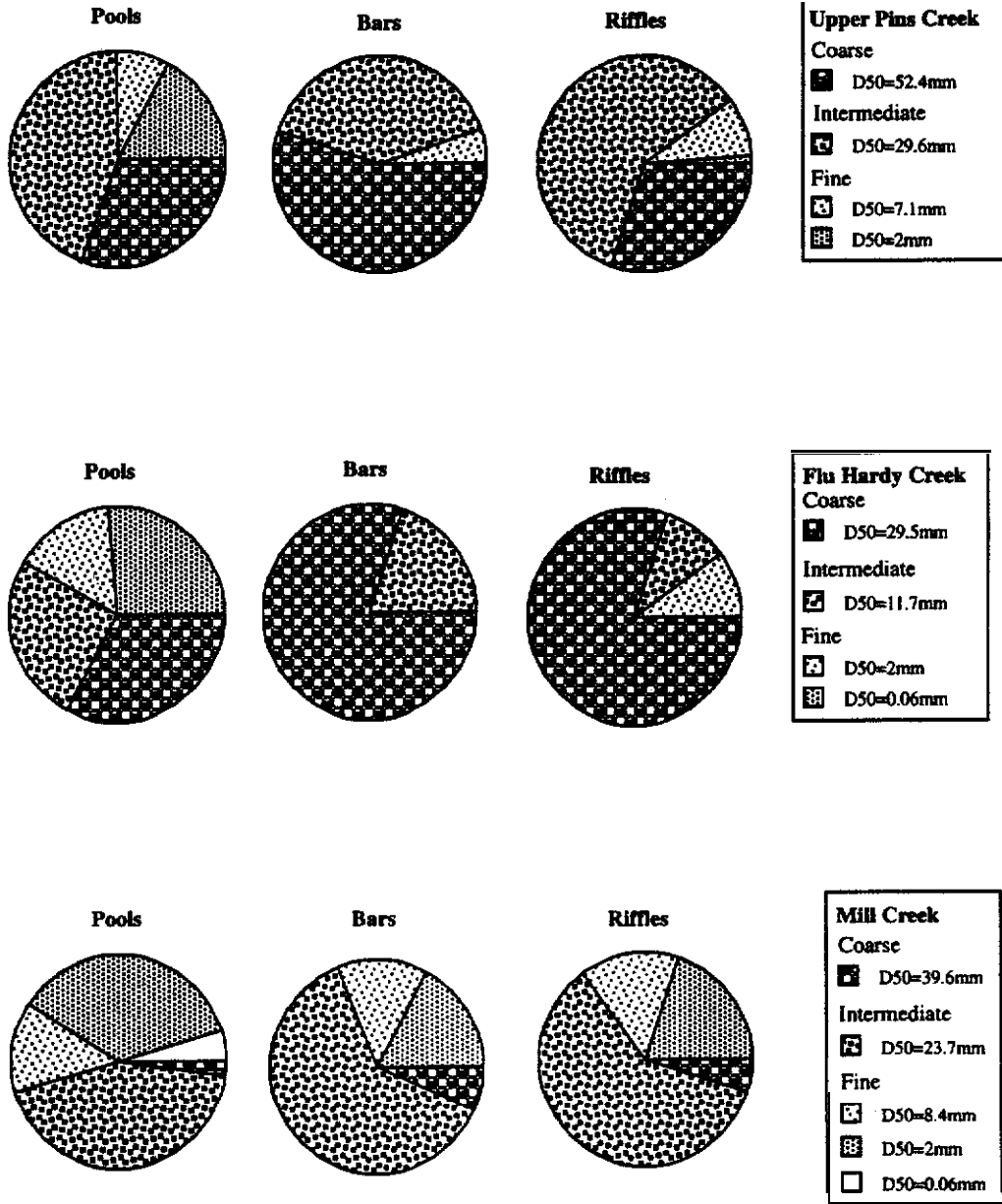


Figure 3.11 cont.

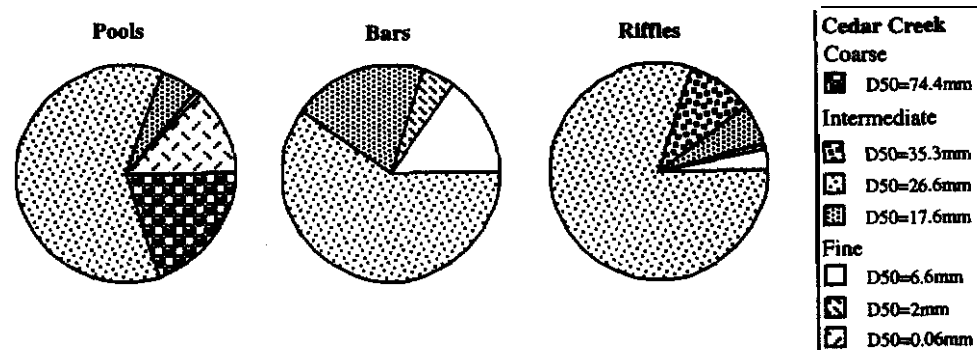
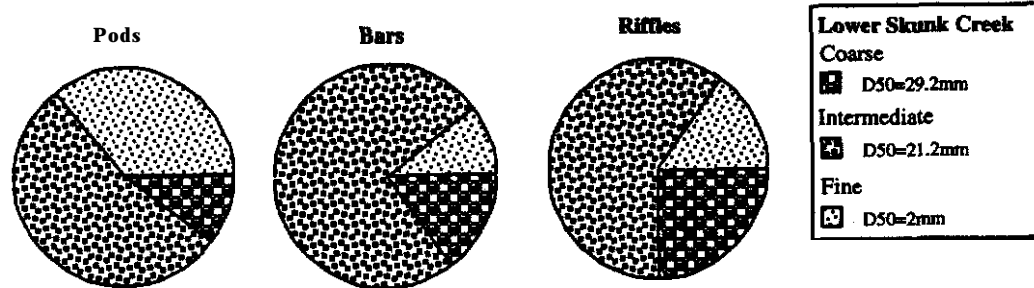
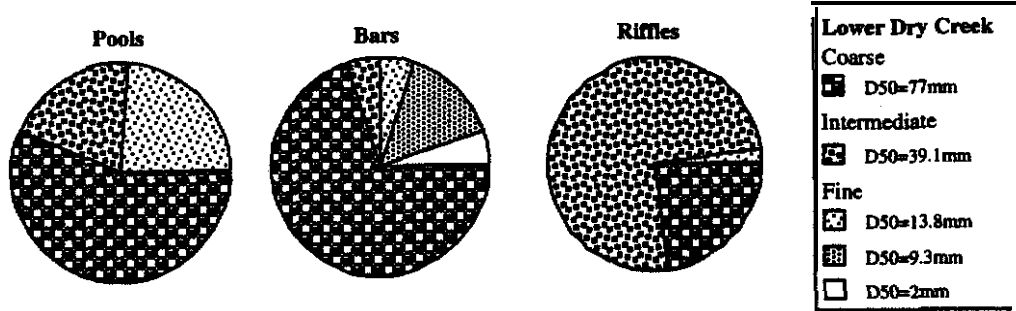


Figure 3.11 cont.

associations, patterns of pool-forming textures differ between the two channel types. Pools are dominantly composed of coarse textures in debris-poor channels, while the majority of pool-forming textures are fine- and **intermediate-grained** in LWD-rich channels. Furthermore, while nearly all of the pools in LWD-poor channels contain coarse grains (found as expected on pool bottoms), the percentage of pools containing coarse grains in LWD-rich streams averages about 63% and can be as low as 13%. Riffles are texturally transitional between pools and bars in both channel types (Fig. 3.11).

For practical reasons, textural mapping was conducted during summer low flow, and because of this it is possible that the finer textures in pools may represent seasonal storage. Fine material is commonly stored in pools between pool-scouting events that are characterized by **bankfull** velocity reversals (Keller, 1971; Lisle, 1979). In such channels the underlying pool bottom is typically coarse-grained, reflecting high **bankfull** shear stresses. During lesser stages, pools **are** typically low energy environments in which **fine** sediment is deposited by waning floods or by low flows capable of mobilizing small exposed grains. Whether fine-grained pool **facies** are seasonal or not, the contrast in **pool-forming** substrate in the two pool-riffle channel types is of more importance, as it suggests fundamental differences in either sediment loading or hydraulic roughness. Lisle and Hilton (1992) found a positive correlation between estimates of sediment supply and the volume of fine-sediment stored in pools, and they proposed an index of this volume, **V***, as an indicator of sediment load. Deposition, however, can occur either due to an increase in sediment supply that exceeds the channel transport capacity or due to a decrease in transport capacity relative to the sediment load. As such, **decreased** transport capacity due to LWD roughness may also induce deposition. Given that it is the LWD-rich channels that exhibit **finer** pool textures, this later explanation is more plausible.

Rather than just **being** representative of seasonal storage, **fine-grained** pool textures may alternatively be a characteristic feature of all stages, including bankfull, in **debris-**

dominated channels. In other words, textural fining in pools may simply be a result of a **reduction** of transport capacity, rather than an exceedence of capacity and consequent deposition, as in the first scenario. Although woody debris is effective at causing flow convergence and constriction that lead to **forced** pool scour, the resistance created by a pool-forming LWD obstruction must simultaneously cause significant momentum extraction at all stages. Consequently, while accelerations around LWD may cause scour and local surface coarsening, it is expected **that** proximal zones of low shear stress characterized by finer textures would also be associated with LWD-forced pools due to debris form drag. This concept is supported by the observation that many of the pools in the debris-rich channels have coarse or intermediate pool bottoms (zone of highest shear stress) and fine-textured pool tails or sidewalls, while the surrounding riffles are typically of intermediate grain size.

A third possible explanation of fine-grained pool textures is suggested by flume studies of Lisle et al. (1993) and **Dietrich** et al. (1989). They found that for conditions of low sediment supply, the active **transporting** zone of the bed is **confined** to a **narrow** corridor of **fine-grained** material surrounded by coarser textures. These textural distinctions result from differential spatial patterns of sediment supply (Dietrich et al., 1993; Lisle et al, 1993). Mobile grains are essentially mined **from** exposed positions on the bed and concentrated into a high sediment supply, fine-textured, transporting zone. Lisle et al. (1993) found that for a pool-riffle morphology this transporting zone coincided with the thalweg, producing fine-textured pools. Because continuous, recognizable, fine-grained corridors were not observed in the Olympic sites this scenario is not considered relevant to the study reaches.

Given that it is the LWD-rich channels that exhibit finer **pool** textures, it seems **likely** that regardless of whether the **finer-grained** textures are seasonal or not they are a response to increased momentum extraction caused by woody debris. Repeated **textural**

mapping throughout the year and during different flow stages would be needed to assess whether finer-grained pool textures are seasonal or not.

Further examination of the reach maps shows a consistent local response of surface textural fining near most LWD, regardless of morphologic association of the debris (Maps 2-5). A section of Flu Hardy Creek (Fig. 3.12) exemplifies the local influence of LWD on surface textures. The dominant surface texture ($D_{50}=29.5$ mm) fines to intermediate ($D_{50}=1.7$ mm) and small ($D_{50}=2$ mm) textures near in-channel LWD. Mechanisms of LWD momentum extraction that cause textural fining include form drag, skin friction, hydraulic jumps, and physical blockage resulting in back-water and **decreased** energy slope. Logs and old-growth **rootwads** with low angles of attack also effectively steer flow, forcing local flow convergence and divergence in a fashion analogous to topographic steering (e.g., **Dietrich** and Smith, 1983). Momentum fluxes associated **with** flow steering alter channel shear stresses, which are in turn reflected by changing textural patterns (e.g., **Dietrich** and Smith, 1984a; **Dietrich** et al., 1979). The fluid accelerations and decelerations resulting from these momentum fluxes implicitly indicate energy loss from the system. Form drag calculations are an engineering approach that approximates the energy lost via these processes, as well as the more abrupt and violent energy dissipation caused by obstructions **with** near-perpendicular attack angles. As such, when I speak of LWD form drag it should be recognized that I am invoking a broad variety of styles of energy dissipation.

Effectiveness of LWD as an energy dissipater depends on its **size**, orientation, and position within the flow column. For example, although the farthest downstream log in Figure 3.12 is significantly larger than the next two upstream ones, **the** orientation of the upstream logs perpendicular to flow causes a stronger textural and morphologic response. Flow constriction around the perpendicular logs forces the formation of a channel-spanning underscour pool, but also results in proximal textural fining due to the high form drag of

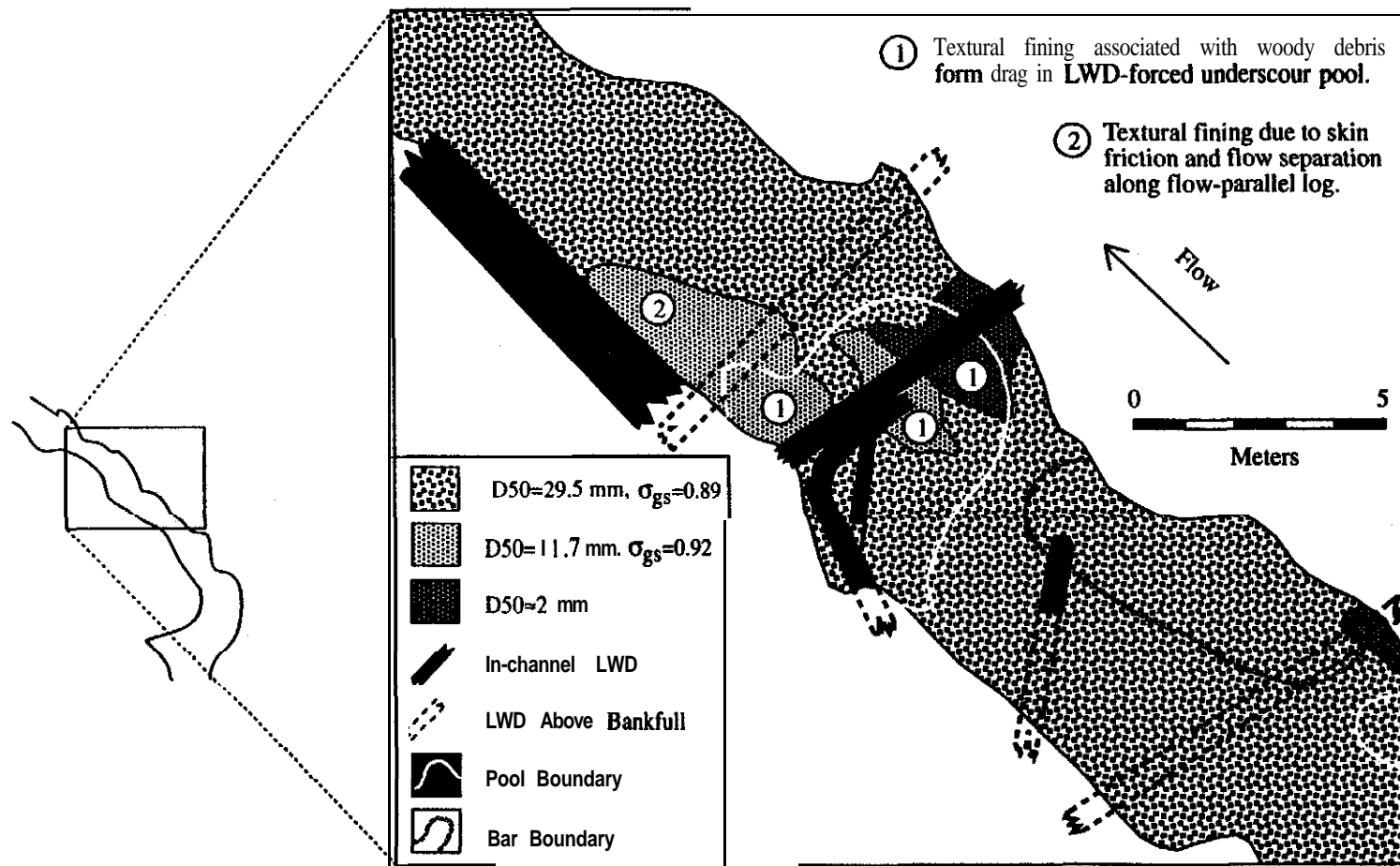


Figure 3.12 Section of Flu Hardy Creek showing mapped surface textures, LWD, and channel units. Surface textures are locally responsive to in-channel LWD (see numbered notes in the figure).

the LWD. The other two logs in this pool play a subordinate role to both textural and morphologic response (see discussion in Montgomery et al. (in **press**) regarding classification and **identification** of LWD morphologic function). Skin friction and flow separation along the large, downstream, flow-parallel log also induce textural fining, however persistence of fining to the downstream end of the log may be inhibited by channel narrowing and flow constriction, as well as by a local steepening of slope associated with a morphologic transition from pool to riffle (Fig. 3.12). The farthest upstream in-channel log has no textural effect, because of a much greater pitch than the other in-channel pieces, resulting in only a small portion of the log interacting with the flow.

Textural response to channel-spanning LWD jams has been documented by Rice (1990; 1994) in channels on the Queen Charlotte Islands of British Columbia. Rice (1994) proposed a cycle of textural response due to LWD regulation of sediment supply. As a LWD jam becomes established there is a progressive upstream damming and fining of sediment and a downstream deprivation and coarsening. Failure of the jam over time releases the upstream stored fines, completing the cycle by causing a progressive downstream **fining** and upstream coarsening. No effective wood jams were present at the Olympic study sites and so this style of textural response was not observed; rather, textural response occurred locally due to energy dissipation associated with relatively discrete LWD obstructions.

In addition to affecting local surface textures, LWD provides a significant control on channel morphology in forest streams (Zimmerman et al., 1967; Keller and Swanson, 1979; Lisle, 1986b; Smith and Buffington, in press; Montgomery et al., in press). The Olympic data agree quite well with the findings of Montgomery et al. (in press), which show that pool spacing in forest channels is inversely related to LWD frequency (pieces/m) (Fig. 3.13). The LWD-poor pool-riffle channels straddle Montgomery et al.'s (in press)

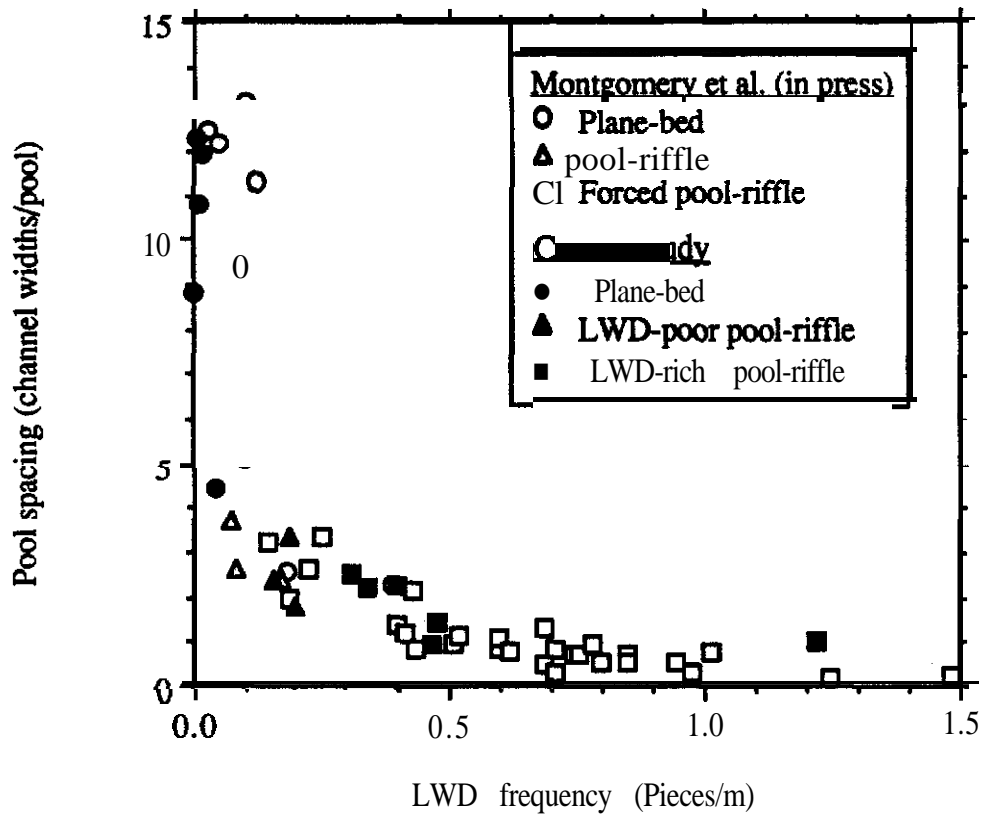


Figure 3.13 Pool spacing (number/channel width of stream length) as a function of LWD frequency (pieces/m). The Olympic data are typical of other Pacific Northwest and southeast Alaskan channels, all exhibiting similar morphologic response to LWD frequency. Montgomery et al. (in press) further detail the controls on pool spacing in forest channels.

TABLE 35: Pool Characteristics and LWD Abundance of the Olympic Channels

Channel	Pool Type			Pool Spacing (channel widths/pool)	LWD/m ²	LWD/m
	Self- formed (#)	LWD- forced (#)	Boulder- forced (#)			
<i><u>Plane-bed</u></i>						
Upper Dry Creek				>8.8	0.000	0.00
Alder Creek				>10.8	0.001	0.01
Hoko Tributary		1		12.0	0.003	0.02
Lower Hoh Slough	1			12.3	0.001	0.01
Upper Hoh Slough		1	1	4.5	0.004	0.04
<i><u>LWD-poor Pool-riffle</u></i>						
Upper Skunk Creek	2	3		2.4	0.023	0.16
Hoko River	3	4		1.4	0.01s	0.20
Lower Pins Creek	2	1		3.3	0.029	0.19
<i><u>LWD-rich Pool-riffle</u></i>						
Upper Pins Creek		5		2.3	0.065	0.40
Flu Hardy Creek	2	2		2.5	0.045	0.31
Mill Creek	2	6		1.0	0.140	1.22
Lower Dry creek		4		2.2	0.043	0.34
Lower Skunk Creek	2	9		1.0	0.036	0.47
Cedar Creek	2	4		1.5	0.042	0.48

self-formed and LWD-forced pool-riffle data, while the debris-rich pool-riffle **channels** plot with their LWD-forced data. Table 3.5 shows that most pools in the Olympic pool-riffle channels are LWD-forced, even in the debris-poor streams. Given this last observation it is not readily clear why the pools in debris-poor **channels** do not behave analogously to those of LWD-rich **channels** and exhibit a majority of fine and intermediate pool-forming textures. It may be that there are more pieces of LWD per pool, and thus more local energy dissipation, in the debris-rich channels, or it may be that higher wood loading provides greater reach-wide energy dissipation and a higher probability of significant textural response at pool-forming obstructions.

Differences in patterns and morphologic associations of textures emphasize process distinctions between obstruction-free and debris-loaded pool-riffle channels. Textural patterns in free-formed pool-riffle channels reflect topographically-induced spatial distributions of shear stress. Surface textures in debris-loaded pool-riffle channels additionally indicate LWD-induced redistribution and dissipation of channel shear stresses.

Subsurface Textures of the Olympic Channels

Subsurface grain size distributions for each layer (i.e., **10 ℓ** volume) sampled below pebble-counted textural patches are presented in Figure 3.14, and Table 3.6 lists the corresponding D_{50ss} and σ_{gss} values. Subsurface samples were analyzed by layer in order to investigate textural variation with depth. Grain size distributions of textures were similar with depth in some channels (Fig. **3.14g**, i, p, q, s, t). but in others were highly variable (Fig. **3.14b**, d, h). Textures with variable subsurface distributions at depth demonstrate the need to sample a sufficient volume of sediment if a representative census is to be obtained, reinforcing the sampling criterion of Church et al. (1987).

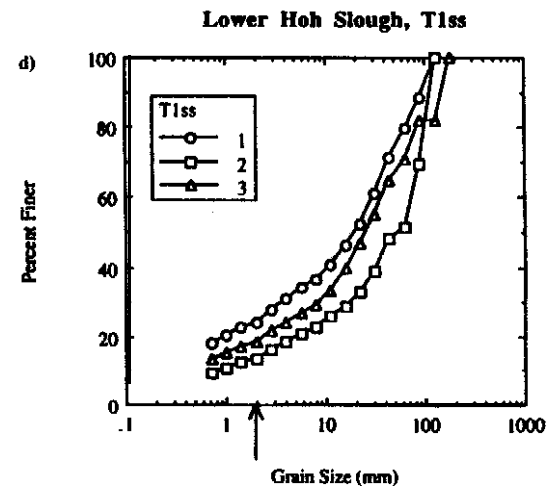
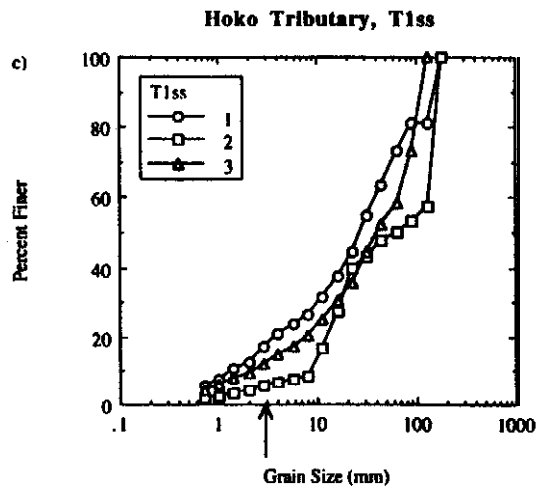
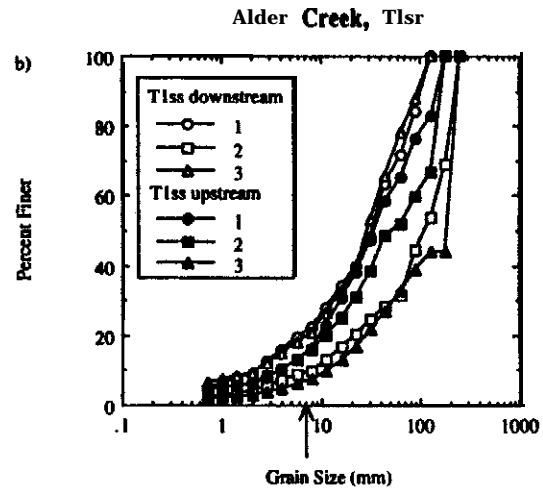
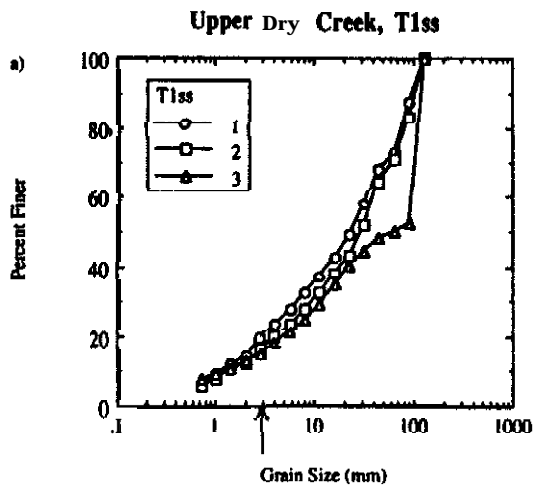


Figure 3.14 Subsurface grain size distributions of textures sampled in the Olympic channels. Grain size distributions are shown for each layer (10 ℓ bucket) sampled. Abscissa arrow indicates calculated reach-average $D_{s_{us}}$ value.

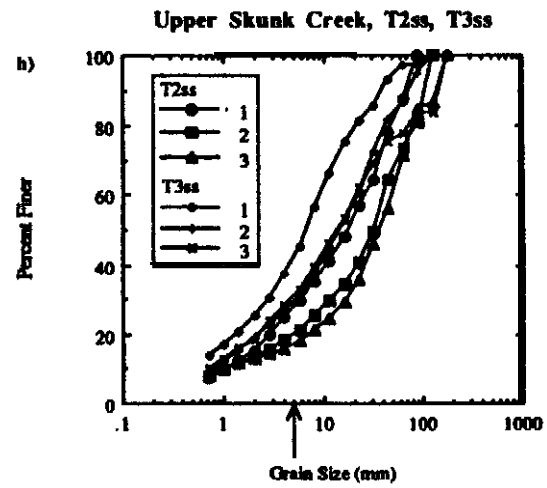
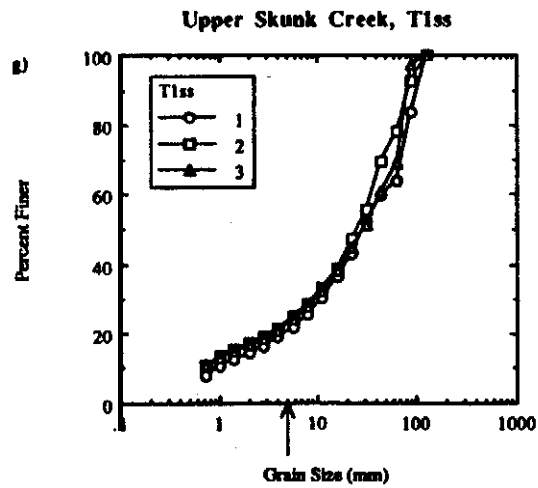
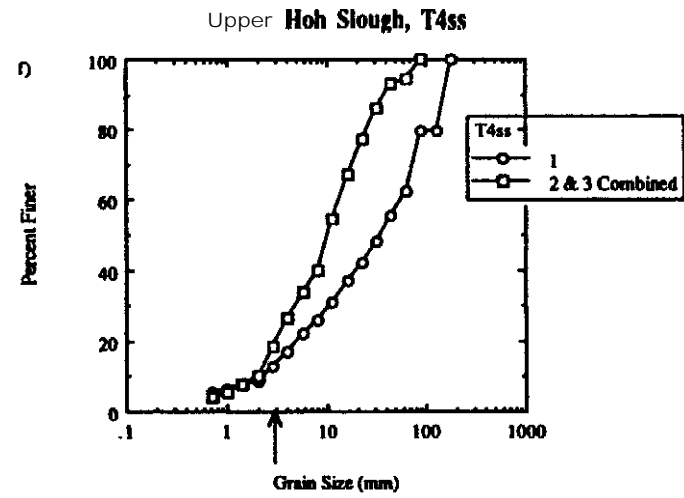
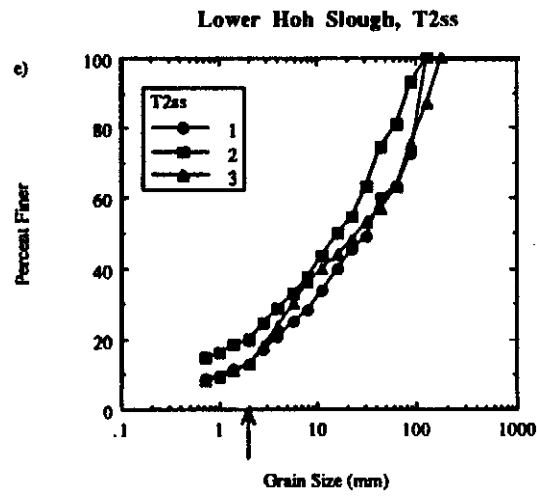


Figure 3.14 cont.

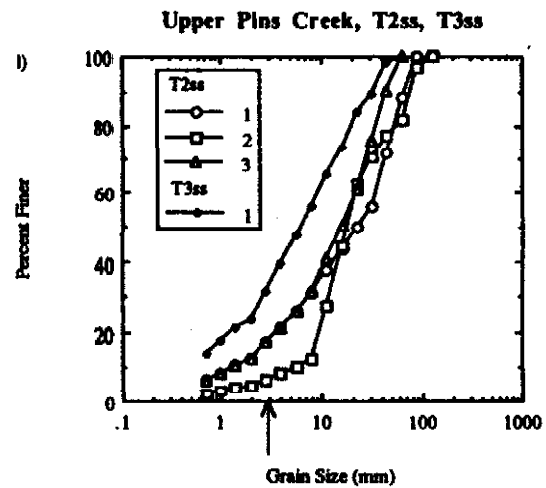
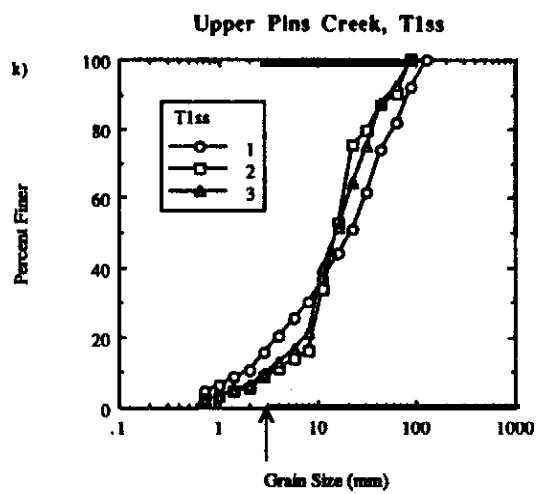
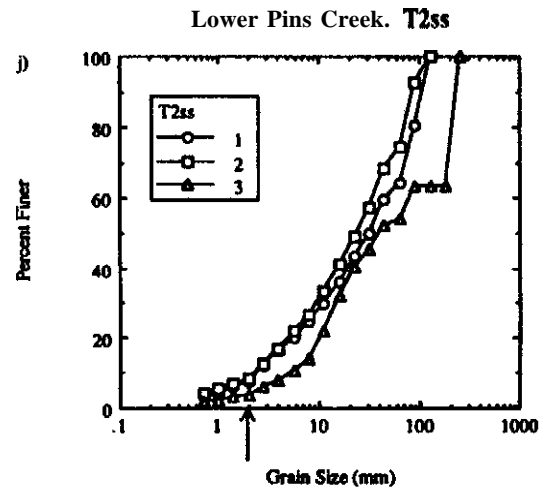
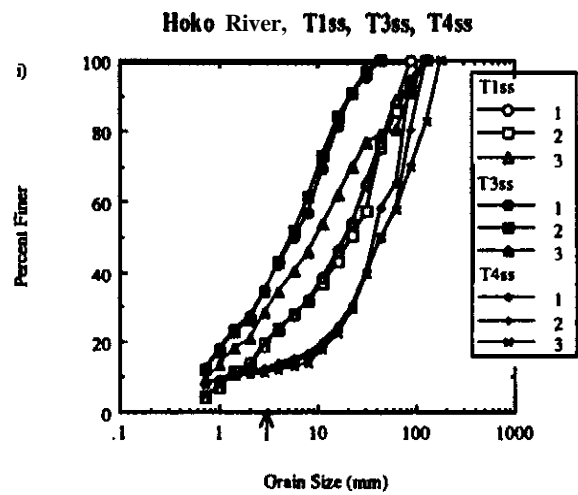
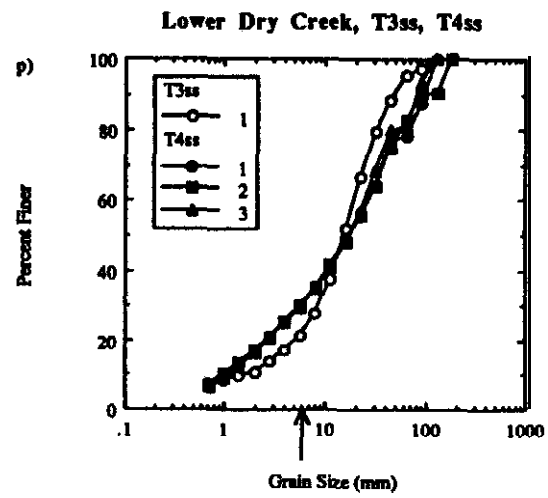
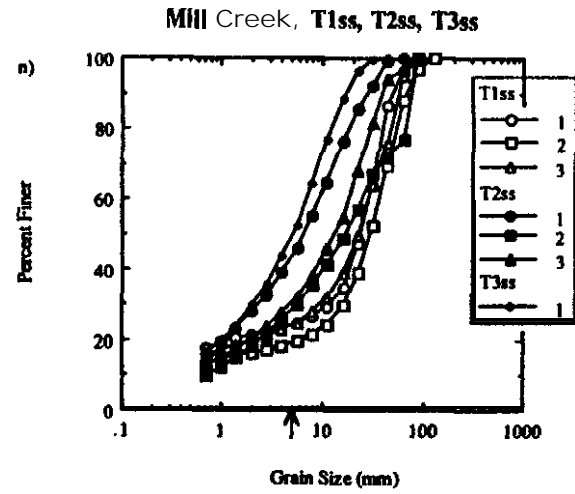


Figure 3.14 cont.



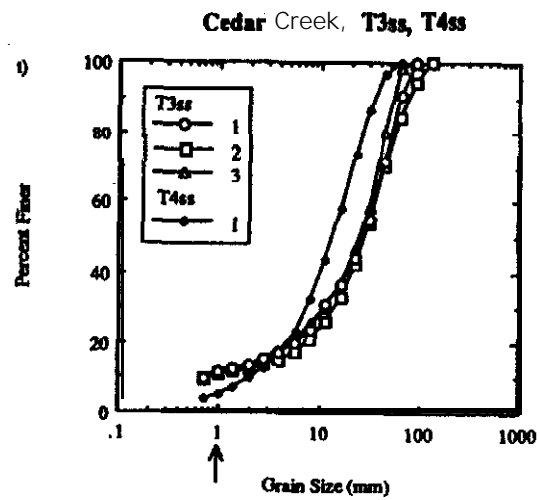
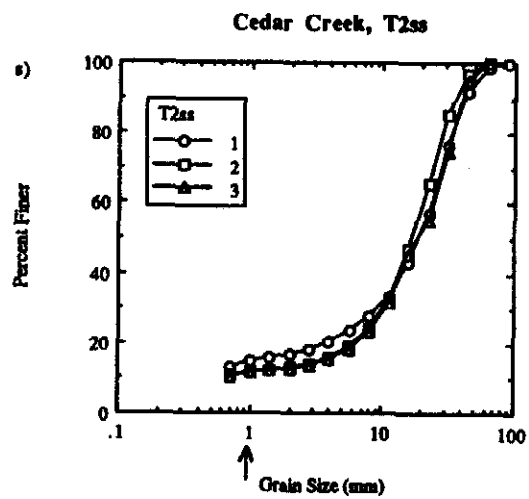
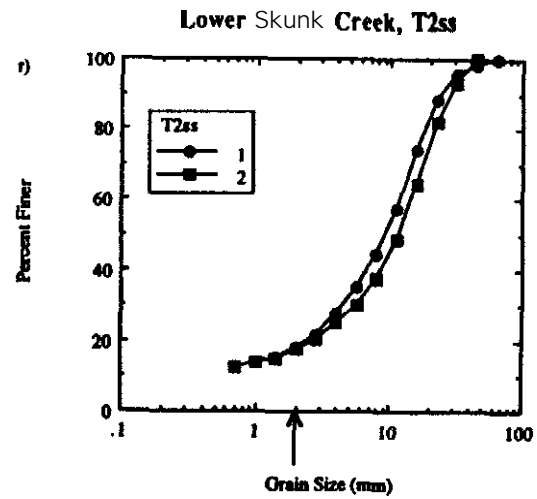
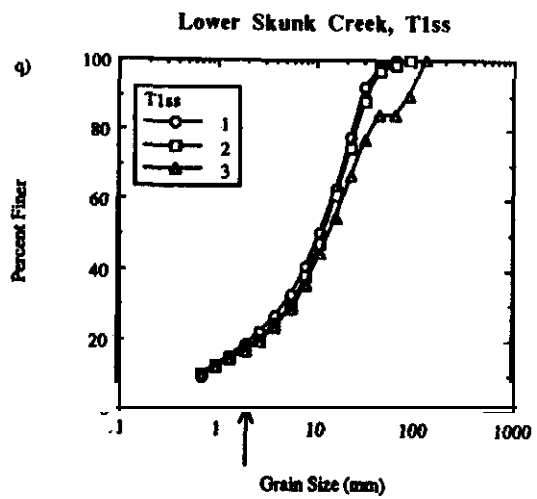


Figure 3.14 cont.

TABLE 3.6: Olympic Subsurface Grain Sii By Sample Layer

Channel	Texture [§]	D _{50ss} (mm) [†]	σ _{gss} (φ)	
<i><u>Plane-bed</u></i>				
Upper Dry creek	T1.1	23.4	2.60	
	T1.2	29.8	2.54	
	T1.3	62.6	2.58	
Alder Creek	T1ds.1	33.4	2.23	
	T1ds.2	111.6	1.91	
	T1ds.3	29.5	2.06	
	T1us.1	34.9	2.06	
	T1us.2	51.9	2.11	
	T1us.3	188	1.72	
Hoko Tributary	T1.1	21.2	2.86	
	T1.2	62.3	1.93	
	T1.3	41.2	2.23	
Lower Hoh Slough	T1.1	19.6		
	T1.2	55.8	2.64	
	T1.3		3.42	
	T2.1	25.84	2.68	
	T2.2	32.7^{5.8}	3.02	
	T2.3	25.6	2.19	
Upper Hoh Slough	T1, same as lower Hoh slough	T1		
	T1, same as lower Hoh slough	T2.1	25.1	
	T4.2 & 3	10.2	1.77	
<i><u>LWD-poor Pool-riffle</u></i>				
Upper Skunk Creek	T1.1	29.3	2.55	
	T1.2	25.2	2.15	
	T1.3	29.6	2.12	
	T2.1	11.3	2.37	
	T2.2	32.3	2.51	
	T2.3	36.1	2.24	
	T3.1	6.6	2.49	
	T3.2	13.6	3.26	
	T3.3	14.3	2.57	
	Hoko River	T1.1	18.8	2.28
		T1.2	22.3	2.38
		T1.3	19.1	2.26
		T3.1	5.1	1.98
T3.2		5.2	1.94	
T3.3		9.6	2.94	
T4.1		38.7	1.78	
T4.2		46.4	1.77	
T4.3		45.5	1.87	
Lower Pins Creek		T2.1	31.8	2.30
	T2.2	23.5	2.18	
	T2.3	40.5	2.32	
<i><u>LWD-rich Pool-riffle</u></i>				
Upper Pins Creek	T1.1	21.5	2.30	
	T1.2	15.2	1.18	
	T1.3	15.4	2.45	

[§]Textures correspond with those given in Table 3.4. Number after decimal signifies sample layer relative to the surface. ds=downstream, us=upstream.

[†] Grain size distributions are untruncated.

TABLE 3.6 cont.

Channel	Texture ^{\$}	D _{50ss} (mm) [†]	σ _{gss} (φ)
	T2.2	17.7	2.24
	T2.3	15.7	3.11
Flu Hardy Creek	T3.1	6.2	2.35
	T1.1	20.5	2.19
	T2.1	14.6	2.18
Mill creek	T1.1	70.039	1.94
	T2.1	---	---
	T1.2	30.9	2.56
	T1.3	22.8	2.66
Lower Dry Creek	T2.1	6.7	---
	T2.2	17.0	2.74
	T2.3	13.2	2.43
	T3.1	5.2	2.01
	T1.1	57.5	2.21
	T1.2	58.0	2.61
	T1.3	82.1	2.35
	T2.1	---	---
	T2.2	30.7	1.67
Lower Skunk Creek	T2.3	15.3	2.73
	T3.1	---	1.71
	T1.1	11.1	2.05
	T1.2	12.1	2.05
	T1.3	13.7	2.31
	T2.1	9.2	1.87
	T2.2	11.6	1.95
Cedar Creek	T2.1	19.0	2.32
	T2.2	16.9	1.48
	T2.3	19.0	1.55
	T3.1	27.6	2.06
	T3.2	56.5	3.27
	T3.3	28.7	1.86
	T4.1	13.2	1.50

^{\$}Textures correspond with those given in Table 3.4. Number after decimal signifies sample layer relative to the surface. ds=downstream, us=upstream.

[†] Grain size distributions are untruncated.

TABLE 3.7: Subsurface **Textural Composition** of the Olympic Channels

channel	Reach D_{50ss} (mm)‡	Texture	% of Bed	Bulk Textural D_{50ss} (mm)‡	$I\sigma_{gss} (\phi)$ ‡
<i>Plane-bed</i>					
Upper Dry Creek	30.2 (42.5)	T1	100	30.2 (42.5)	2.65 (1.77)
Alder Creek	60.2 (75.8)	T1	100	60.2 (75.8)	2.19 (1.70)
Hoko Tributary	38.2 (47.4)	T1	100	38.2 (47.4)	2.18 (1.87)
Lower Hoh Slough	28.1 (39.7)	T1	63	31.1 (42.3)	3.20 (1.80)
		T2	35	24.2 (35.0)	2.76 (2.21)
		T3	2	~2.0† (na)	
Upper Hoh Slough	14.0 (22.4)	T1	4	31.1 (46.2)	3.20 (1.58)
		T2	0.5	24.2 (40.1)	2.76 (1.95)
		T3		~2.0† (na)	
		T4	11.5	13.7 (21.3)	2.33 (1.64)
<i>LWD-poor Pool-riffle</i>					
Upper Skunk Creek	23.5 (37.9)	T1	71.24	27.8 (40.6)	2.68 (1.40)
		T2	8.22	28.5 (38.3)	2.45 (1.43)
		T3	11.19	10.6 (20.7)	2.67 (1.70)
		T4	9.33	~2.0† (na)	
Hoko River	21.7 (29.8)	T1	61.58	19.9† (28.6)	2.3 (1.49)
		T2	5.10	-6.0† (?)	
		T3	13.87	6.5 (11.9)	2.30 (1.41)
		T4	19.45	42.3 (52.7)	1.76 (1.23)
Lower Pins Creek	30.3 (34.3)	T1	2.58	12.7† (13.3)	1.15 (1.10)
		T2	92.11	32.1 (36.0)	2.52 (2.24)
		T3	4.15	9.2† (9.8)	1.32 (1.19)
		T4	1.16	~2.0† (na)	
<i>LWD-rich Pool-riffle</i>					
Upper Pins Creek	15.5 (19.4)	T1	40.61	16.0 (18.1)	1.65 (1.29)
		T2	48.47	17.9 (21.0)	1.81 (1.35)
		T3	3.22	6.2 (11.5)	2.15 (1.40)
		T4	7.71	-2.0† (na)	
Flu Hardy Creek	10.6 (17.5)	T1	80.53	12.5 (17.8)	2.20 (1.26)
		T2	3.70	7.0 (10.4)	1.94 (0.98)
		T3	11.79	-2.0† (na)	
		T4	3.98	-0.06† (na)	
Mill Creek	10.1 (19.5)	T1	8.15	25.4 (32.4)	2.69 (0.92)
		T2	62.57	11.3 (19.6)	2.58 (1.42)
		T3	11.77	5.2 (9.8)	1.81 (0.83)
		T4	15.89	~2.0† (na)	
		T5	1.63	-0.06† (na)	

‡ Values in parentheses are derived from grain size distributions truncated at D_{sus} and are thus indicative of bedload material only.

† D_{50ss} assumed equal to D_{50s} .

‡ Bedload and suspended load material could not be differentiated as the calculated D_{sus} value is < 2 mm, the minimum resolution used for surface pebble counts: all grain sizes ≤ 2 mm were lumped into one category and are consequently undifferentiable.

TABLE 3.7 cont

Channel	Reach D_{50ss} (mm) [‡]	Texture	% of Bed	Bulk Textural D_{50ss} (mm) [‡]	$I\sigma_{gss} I(\phi)$ [‡]
Lower Dry Creek	41.1 (55.7)	T1			
		T2	47.68 39.28	60.9 26.0 (43.6)	2.42 2.66 (1.17) (1.45)
		T3	7.52	15.3 (19.7)	1.71 (1.06)
		T4	4.79	17.2 (31.4)	2.63 (1.46)
		T5	0.94	~2.0 [†] (na)	
Lower Skunk Creek	9.4 (13.6)	T1			
		T2	62.31 21.54	122 10.3 (15.8) (12.8)	2.11 1.90 (1.30) (1.11)
		T3	16.15	~2.0 [†] (na)	
Cedar Creek	20.6 (24.6)	T1			
		T2	7.53 64.19	74.43 (1.3)	0.89 1.75 (1.05)
		T3			
		T4	6.15 12.80	27.1 13.2 (32.0) (144)	1.97 1.50 (1.33) (1.28)
		T5	2.64	~2.0 ^{†*}	
		T6	1.08	6.6 ^{†*}	0.98
		T7	5.61	~0.06 [†] (na)	

[‡] Values in parentheses are derived from grain size distributions truncated at D_{sus} and are thus indicative of bedload material only.

[†] D_{50ss} assumed equal to D_{50s} .

^{*} Bedload and suspended load material could not be differentiated as the calculated D_{sus} value is < 2 mm, the minimum resolution used for surface pebble counts; all grain sizes ≤ 2 mm were lumped into one category and are consequently undifferentiable.

Median subsurface grain sizes for each bulk subsurface sample are shown in Table 3.7. Sand and **silt-sized** patches were not sampled, as it was assumed that surface and subsurface grain sizes would be negligibly different. Several other **textures** were not sampled, because of insufficient dry exposure; these samples were also assumed to have equivalent surface and subsurface distributions. Of those textures sampled the weight percent of the largest subsurface grain varied from 0.5 to 16.1% of the total weight, with a median value of 3.6%. Consequently, the sampling technique employed generally **underestimated** the volume of material necessary to produce the intended D_{maxss} weight percent of II. Because of the particular sampling technique used, D_{maxss} values less than 1% of the total weight may result from $D_{maxss} > D_{maxs}$, $D_{maxss} > 83$ mm, or samples with significant porosity. While a median D_{maxss} weight percent of 3.6 is acceptable, traditional field weighing of samples is recommended to avoid potentially erroneous assumptions and yield samples with uniform D_{maxss} weight percents.

As expected, reach average D_{50ss} values (Table 3.7) are less than the corresponding surface median grain sizes (Table 3.4), except for two channels; Alder and Lower Hoh have composite **bedload** and suspended load values of $D_{50s} < D_{50ss}$, while Alder and Lower Pins have **bedload** values of $D_{50s} < D_{50ss}$. As with the reach-average results, most of the individual bulk samples show $D_{50ss} < D_{50s}$ (cf. Tables 3.7 and 3.4). However, about 18% of the **bedload** textures and 14% of the composite textures (i.e., **bedload** and suspended load) exhibit subsurface **median** grain sizes greater than that of the surface. **Kinerson** (1990) also found cases of D_{50ss} larger than D_{50s} . Such results may represent insufficient sampling of either of the textural domains, or may occur due to erroneously sampling buried, relict, surface horizons at depth. Bed stratigraphy was not characterized in this analysis, but is a real concern for investigators conducting subsurface sampling; stratigraphy is largely ignored in the subsurface sampling literature, the present study included.

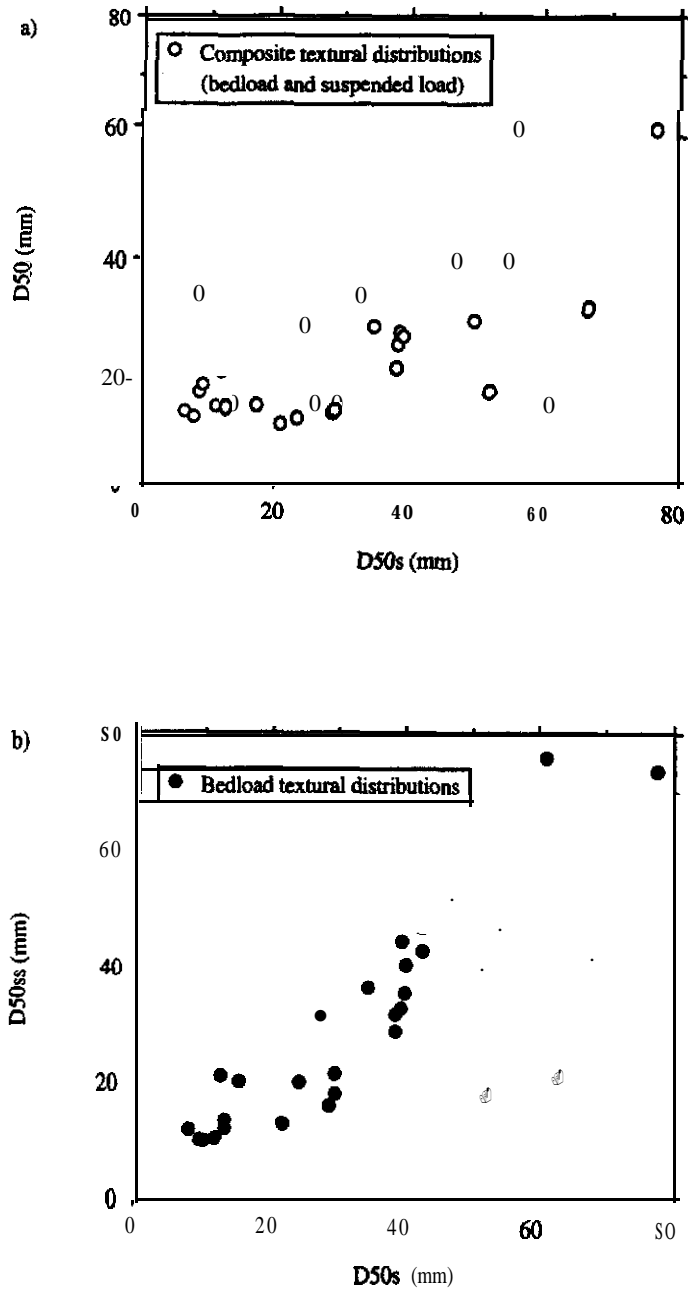


Figure 3.15 Correlation of D_{50s} and D_{50ss} for a) composite and b) **bedload** material of textures surveyed in the Olympic channels.

Although there is considerable scatter in the data, Figure 3.15 shows that D_{50ss} values are roughly correlated with surface median grain sizes. For a given reach, surface textural patches with larger median grain sizes have **correspondingly** larger subsurface median grain sizes (Table 3.7). One might intuitively expect this result **Bedload** material moving through a reach will be sorted by differential shear stresses (e.g., **Dietrich** and Smith, 1984a; **Dietrich** et al., 1979), provided that grain sizes representative of a particular shear stress are available; a higher local shear stress will not have a correspondingly larger **bedload** grain size if larger **sizes are** not available in the supplied **bedload** distribution. As such, subsurface grain sizes [which approximate those of the **bedload** (**Milhous**, 1973; **Kuhnle**, 1993)] should parallel surface grain sizes in expressing the spatial pattern of shear stresses within a reach.

It is commonly assumed that in armored **channels** the surface grain **size** distribution results from winnowing of the parent subsurface distribution (**Carling** and Reader, 1982; **Andrews** and **Parker**, 1987). For this to be true the surface and subsurface grain **size** distributions would share the same range of values. With the lower end of grain **size** distributions truncated uniformly by reach-specific D_{sus} values, comparison of surface and subsurface D_{max} values indicates that 30% of the textures sampled have equivalent upper grain sizes, while 50% have $D_{maxss} < D_{maxs}$ and 20% have $D_{maxss} > D_{maxs}$. Consequently, the majority (80%) of truncated subsurface grain size distributions are equal to or narrower than their surface counterparts. Kinetic sieving (**Sallenger**, 1979; **Rosato** et al., 1987; **Haff**, 1991) may also be a mechanism for creating armored beds through concentration of coarse material at the surface. This mechanism for armor generation would deplete the subsurface of coarse material, resulting in grain **size** distributions narrower than that of the surface, which is the most common condition observed at the Olympic study sites.

Reach-Average Textural Response Within the Threshold Model Framework: Empirical Results and Preliminary Analysis of Relative Magnitudes of Influence

The **bankfull** threshold model is based on reach-average characterization of channel attributes. While examination of local textural response is important for **understanding** process mechanics, individual textural patches are indicative of particular site-specific conditions that are not easily predicted. As such, a reach-average focus is necessary for prediction of surface grain size and examination of textural response. **Although** mapped surface textures show locally intensive response to flow obstructions, it is likely that turbulent mixing characteristic of natural rivers and accentuated by LWD is **sufficient** to cause momentum exchange **across** textural patches, resulting in a range of obstruction influence broader than the obvious proximal textural responses. Turbulent mixing thus provides a mechanism for integrating local effects into a reach-wide channel response to roughness elements, providing a conceptual linkage between local and reach-scale channel processes.

Reach-average Olympic and Alaskan field data analyzed within the threshold model framework agree well with the hypothesized trends of textural response expressed by Figure 1.1. Within the model construct, study sites segregate by **channel** type into distinct zones of reach-average textural response (Fig. 3.16). As expected, increasing hydraulic roughness produces a systematic textural **fining** and decrease in reach-average **D_{50s}**. **Plane-bed** channels are characterized by grain roughness only and generally plot closest to the threshold channel prediction, while debris-poor pool-riffle channels with **grain, bedform,** and minimal LWD roughness cluster below the plane-bed streams. LWD-rich pool-riffle channels characterized by grain, **bedform,** and abundant woody debris roughness show the strongest textural response and cluster at the bottom of Figure 3.16. Four of the Alaskan channels have morphologies transitional between plane-bed and pool-riffle channel types.

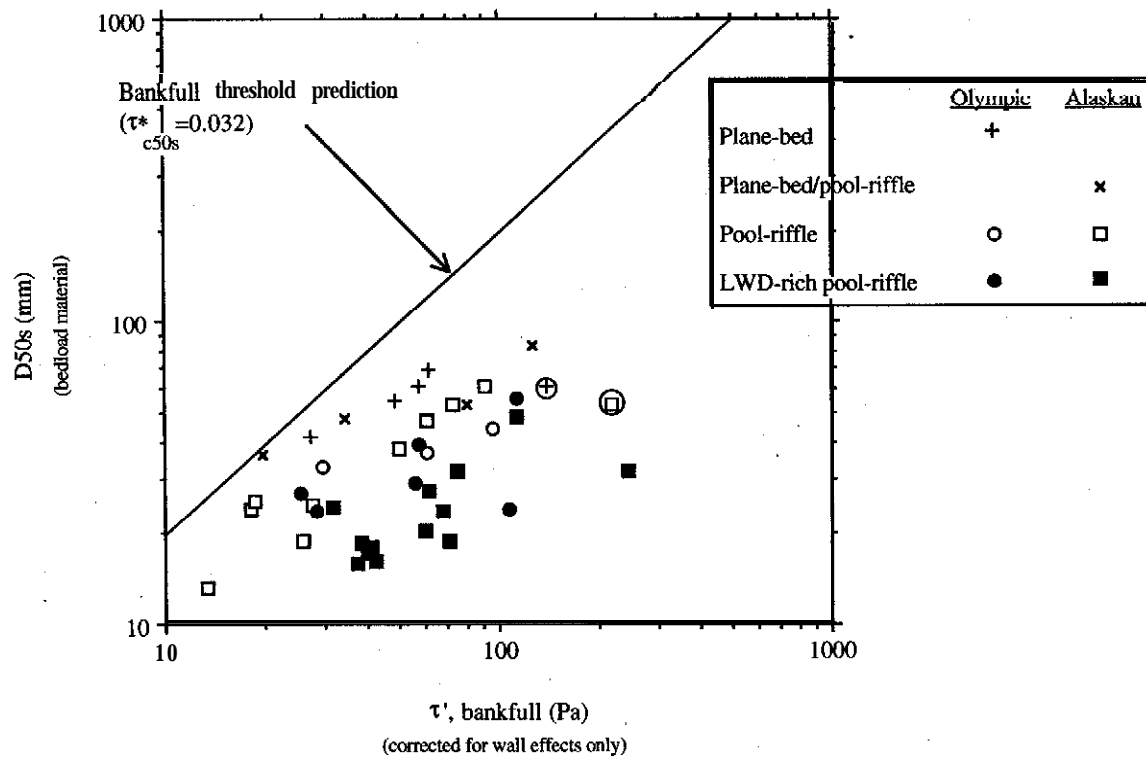


Figure 3.16 Reach-average D_{50s} values (bedload material only) of the Olympic and Alaskan study sites relative to the bankfull threshold prediction of median surface grain size. Abscissa values of τ' are corrected for τ_w only. Note the distinct zones of textural response for plane-bed, LWD-poor pool-riffle, and LWD-rich pool-riffle channels. These zones represent a progressive textural fining and deviation from the model predictions with increasing channel roughness embodied by the channel types examined. Circled data points are channels most recently impacted by catastrophic sediment inputs.

Two of these transitional channels behave like plane-bed streams and plot close to the **bankfull** threshold prediction (Fig. 3.16).

Of the **five** channels showing field evidence of catastrophic sediment inputs, only Alder Creek and Lower Greens Creek (circled points, Fig. 3.16) deviate from the textural response **ranges** of their respective **channel** types. Alder Creek, an Olympic plane-bed channel, has riparian margins inundated by recent debris flow deposits **and** shows a stronger magnitude of textural fining than the other plane-bed channels (Fig. 3.16). This larger degree of **fining** may be due to elevated sediment loads as a result of debris flow disturbance; field observation indicates that the **Alder** Creek debris flow deposited a short distance downstream of the study reach. The morphology of Alder Creek may also be responsible for an **anomalously** low reach-average **D_{50s}**. Alder Creek is a high-gradient, bouldery stream with a morphology verging on that of a cascade channel [definition of Montgomery **and** Buffington (1993)], evidenced by tumbling and tortuous flow over and around individual boulders. This style of turbulent, tumbling, jet-and-wake flow, different from the other plane-bed channels examined, significantly increases downstream energy dissipation (Chin, 1989) and may explain the low observed **D_{50s}**. The study reach of Lower Greens **Creek**, an Alaskan LWD-poor **pool-riffle** channel, lies just downstream of a recent, large landslide that entered **and** dammed the channel; the failure was initiated downslope of a mining road. The Lower Greens Creek data used here were collected a short time **after** the landslide dam was breached. Stored sediment liberated by the dam failure would have led to increased downstream sediment loading and may explain the larger magnitude of fining in this **channel** compared to the other LWD-poor pool-riffle channels. However, about 25% of Lower Greens Creek is composed of step-pool channel units containing two 1-1.5 m bedrock steps (falls): turbulent energy dissipation associated with these **channel units** may contribute to the low **D_{50s}** observed in this channel.

Of the landslide-affected channels, only the two most recently impacted ones show textural fining of greater magnitude than **channels** of similar morphologic type, suggesting a transient nature of textural response to catastrophic changes in sediment supply. For example, Lower Dry Creek, an Olympic LWD-rich pool-riffle channel, is characterized by relict (now vegetated) channel-margin debris flow terraces, indicating past catastrophic changes in sediment loading. However, Lower Dry Creek has a relatively high **reach-average D_{50s}** compared to the other LWD-rich pool-riffle channels, suggesting little residual influence of any past increases in sediment loading.

While showing no evidence of recent catastrophic sediment impacts, the other thirty-six study sites likely have different levels of sediment loading. Despite these potential differences in sediment supply, Figure 3.16 demonstrates a trend of decreasing reach-average median surface grain size with increasing complexity of channel roughness, **indicating that** non-catastrophic sediment loading is subordinate to **bedform** and LWD roughness at the sites investigated. Although there is the potential for severe sediment impacts, and hence sediment-induced textural fining, in Pacific Northwest channels, natural catastrophic changes in sediment load tend to result from infrequent pulsed events (i.e., debris flows, **fire** storms, **50-** 100 year floods, etc.). Furthermore, because sediment impacts of this sort are typically not sustained, their influence on textural response will be transient compared to the pervasive influence of **bedforms** and LWD in forest channels. Consequently, LWD and stable **barforms** provide long-term influences that dominate surface textures of the study sites, while sediment supply effects are either relatively less significant or transient. The frequency with which channels are impacted by sediment loading, however, depends on geomorphic province and position within a channel network. Higher-gradient channels of the Pacific Northwest tend to be closer to debris flow sources, but lower-gradient channels are likely sites for debris flow deposition (e.g., Montgomery and Buffington, 1993).

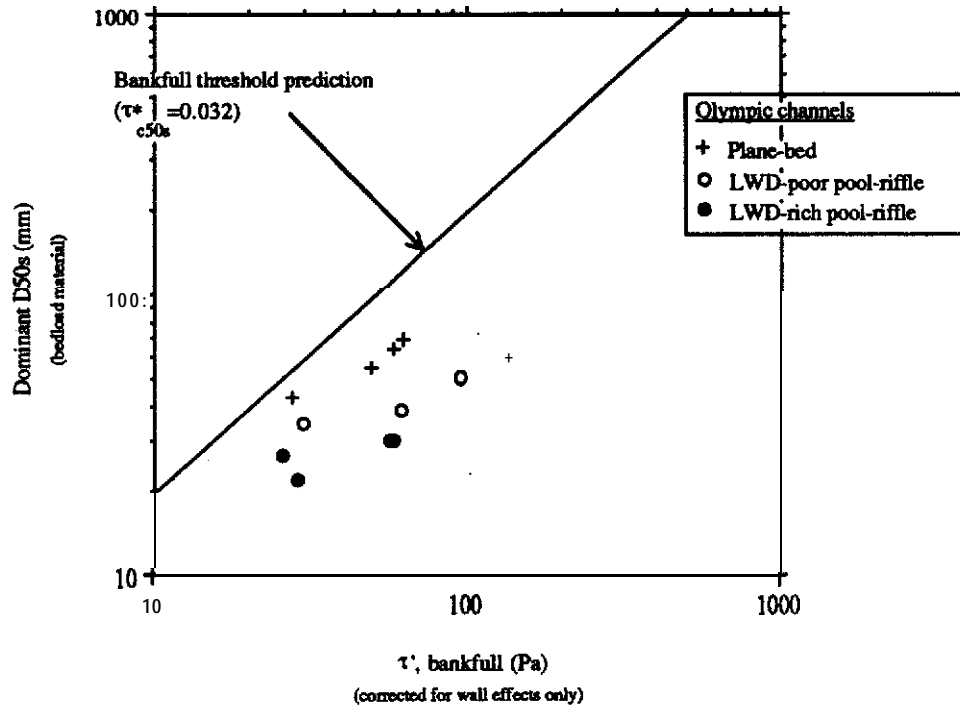


Figure 3.17 D_{50s} values of the dominant (i.e., most abundant) surface texture in each of the Olympic channels plotted relative to the bankfull threshold model prediction. Zones of response generally analogous to those of Figure 3.16 suggest that textural response to hydraulic roughness elements occurs on a reach scale, rather than solely on a local scale proximal to flow perturbances.

To further examine reach-scale textural response, **the** median grain size of the dominant (i.e., most abundant) surface texture of each Olympic channel was plotted versus shear stress (Fig. 3.17). A segregation of research sites by channel type similar to that of Figure 3.16 suggests that hydraulic roughness elements have a reach-wide impact on surface textures and are not just limited to local textural response.

Because Figure 3.16 illustrates a continuum of textural response, some overlap occurs between channel types. However, zones of response associated with specific channel types can be identified. Each zone describes a distribution of textural **response** (Fig. 3.18), with LWD-rich channels showing the broadest range and the highest magnitude of fining, expressed as the ratio of predicted-to-observed median surface grain size. Plane-bed channels exhibit the narrowest response range, but their distribution is based on considerably fewer data, and thus is less well defined.

The **three** types of gravel-bedded streams studied were chosen in order to distinguish textural response to different scales and styles of hydraulic **roughnesses** (i.e., **bedforms** versus LWD). Although LWD was present in both pool-riffle channel types, wood loading in the debris-poor channels is quite low, and for comparative purposes can be considered insignificant (Fig. 3.8). As such, **LWD-poor** pool-riffle channels predominantly represent grain and **bedform** roughness, while debris-rich channels represent **the** full suite of grain, **bedform**, and LWD resistance. Assuming negligible sediment supply effects, the relative magnitudes of textural response due to **bedform** and LWD **roughness** can be examined empirically by comparing median values of the response distributions (Fig. 3.18). These data show that **bedform** and LWD roughness **are** comparable, both causing a roughly two-fold decrease in reach-average median surface grain size. It is emphasized, however, that these magnitudes of textural response are median values of overlapping response distributions. Furthermore, surface textures of the plane-bed channels also deviate somewhat from the **bankfull** threshold prediction of surface

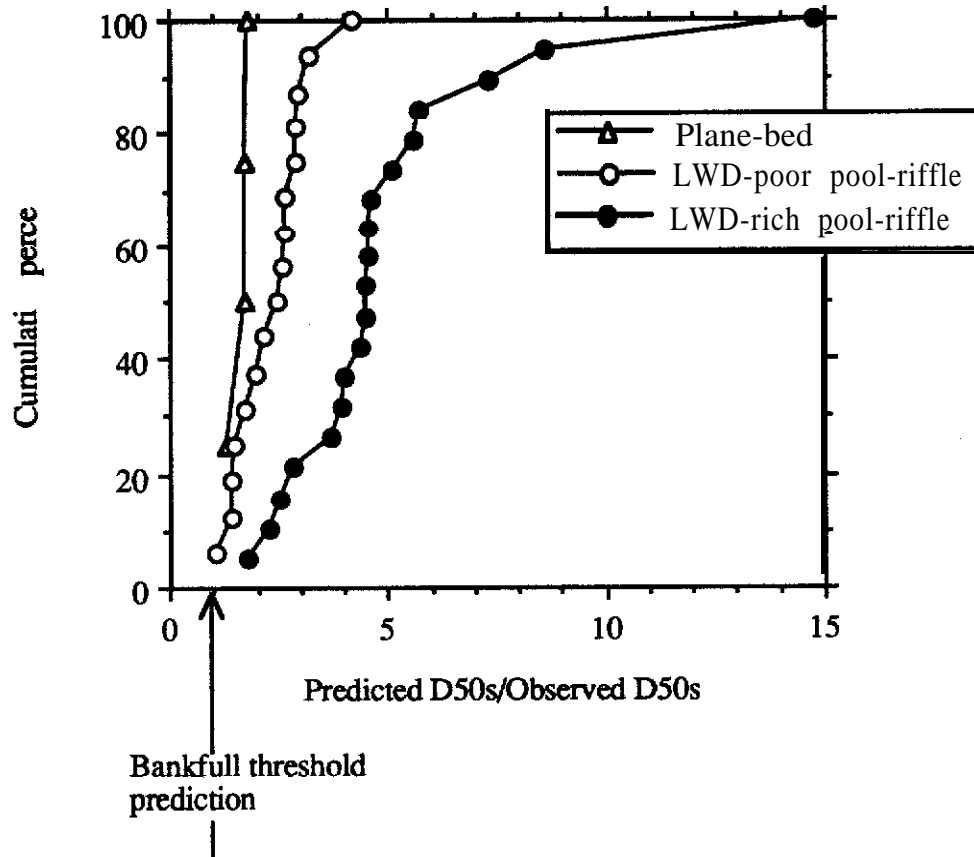


Figure 3.18 Distributions of reach-average textural response in plane-bed, **LWD-poor**, and LWD-rich channels. Textural response is expressed as deviation from unity for the ratio of predicted-to-observed D_{50} s. Due to some **bedform** roughness, the transitional **plane-bed/pool-riffle** channels are included with the LWD-poor pool-riffle data. The **sediment-**impacted Alder Creek and Lower **Greens** Creek are not included here.

gram **size** (Fig. 3.16 and **3.18**), presumably due to background levels of sediment loading. As such, the magnitudes of textural fining due to **bedform** and LWD roughness determined from Figure 3.18 should **be** viewed as estimates, pending more rigorous discrimination of relative effects of sediment supply and hydraulic roughness. It is further cautioned that while relative magnitudes of textural response to **bedforms** and woody debris can **be** assessed from the empirical findings, the absolute degree of textural response inferred from the model is sensitive to the τ^*_{c50s} value used for the model predictions (cf. Fig. **2.2a-b**).

Compatibility of Data Sets

Comparison of the Olympic and Alaskan data is based on the assumption that the methods of reach-average textural characterization are comparable. The two methods employed were: regularly spaced cross-channel pebble counts; and mapping of textural patches, accompanied by representative pebble counts of each texture. The two techniques are obviously identical for mono-textural channels, but for patchy streambeds accurate representation of channel grain sizes through regularly spaced pebble counts depends on **the areal** extent of sampling and the spatial distribution of textures within the channel [see also discussion by Wolcott and Church (1990)]. For example, the number and **areal** extent of pebble counts shown in Figure 3.19 are likely to approximate the true distribution of Figure **3.19a**, but misrepresent that of **Figure 3.19b** simply due to differences in spatial distributions of textural patches in the two cartooned channels. Both estimates can be improved by either increasing the number of cross-channel transects or by increasing the area sampled in each pebble count. The Alaskan pebble counts are estimated to have sampled approximately 1530% of the area of each study reach. This sampling area is probably sufficient for the LWD-rich channels, which have spatial distributions of textures similar to that shown in Figure **3.19a** and Map 3, but is likely to be less accurate for the

debris-poor channels, as they typically have less well-distributed textural patches. Despite the uncertainty associated with the Alaskan LWD-poor channels, the bulk of the grain size data used in this analysis are likely compatible.

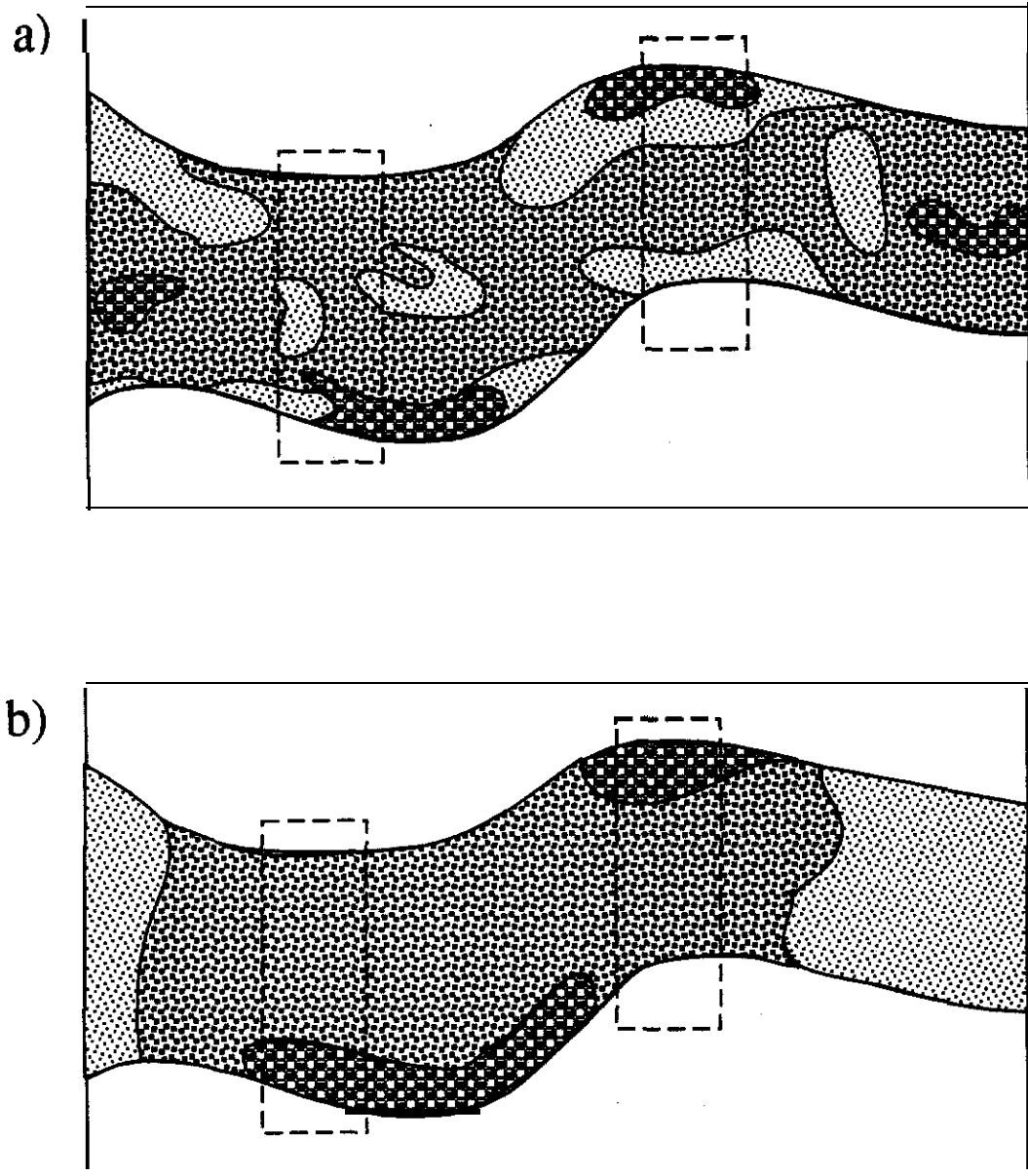


Figure 3.19 Illustration of the effectiveness of discrete pebble counts in a channel with a) highly complex and b) less complex spatial arrangements of surface textures.

Chapter 4: Land Management Implications

ASSESSMENT OF CHANNEL CONDITION AND PREDICTION OF RESPONSE POTENTIAL

Figures 4.1 and 4.2 summarize empirically determined ranges of textural response to **bedform** and LWD roughness inferred from the Olympic and Alaskan field data and also show the range of textural response to sediment supply determined from Kinerson's (1990) data. The empirical response distributions (Fig. 4.2) demonstrate that the combined influences of **bedform** and LWD roughness are of the same magnitude as that of potential textural **fining** due to sediment supply. Consequently, sediment supply and hydraulic roughness are both first-order controls on surface **textures** of forest gravel-bedded channels. If the interpretation made in Chapter 3 is correct, however, sediment supply impacts on surface textures, while potentially significant, may be infrequent and ephemeral compared to the pervasive effects of **bedform** and LWD roughness in forested environments like those studied.

The **bankfull** threshold model coupled with subsurface grain **size** analyses provides a valuable management tool for assessing channel condition. Predicted values of **D_{50s}** and measured values of **D_{50ss}** define theoretical limits of textural response to both sediment supply and other hydraulic roughness elements, as discussed in Chapters 1 and 2. Channel condition in terms of **the** degree of existing textural response to these factors can be assessed by comparing **the** observed textural fining relative to that of the potential fining represented by the theoretical limits

$$\frac{(\text{Predicted } D_{50s} - \text{Observed } D_{50s})}{(\text{Predicted } D_{50s} - \text{Observed } D_{50ss})} \quad (7)$$

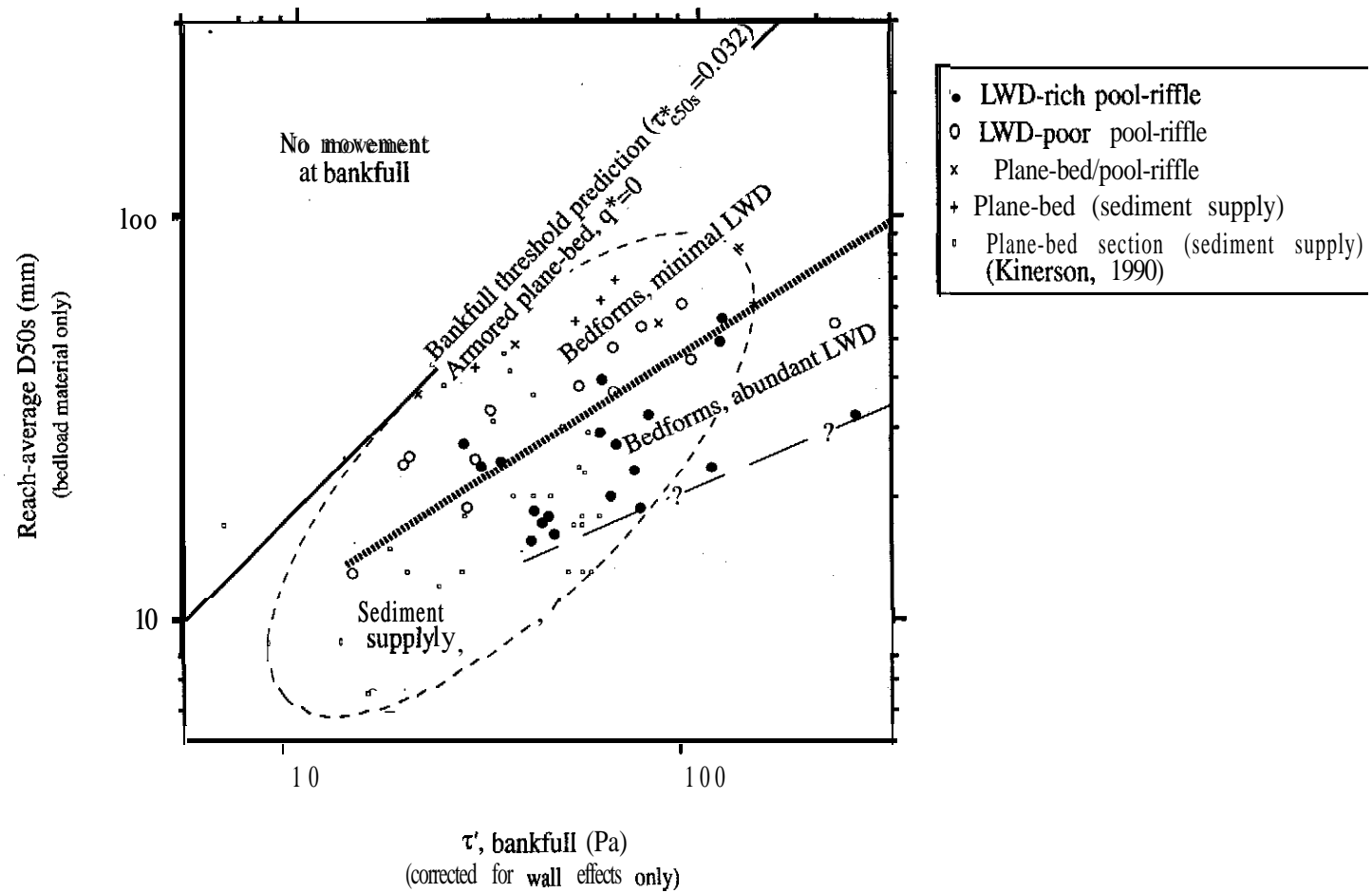


Figure 4.1 Summary of the bankfull threshold model and empirically determined ranges of textural response to sediment supply, bedforms, and LWD. Data are those shown in Figures 2.3 and 3.16.

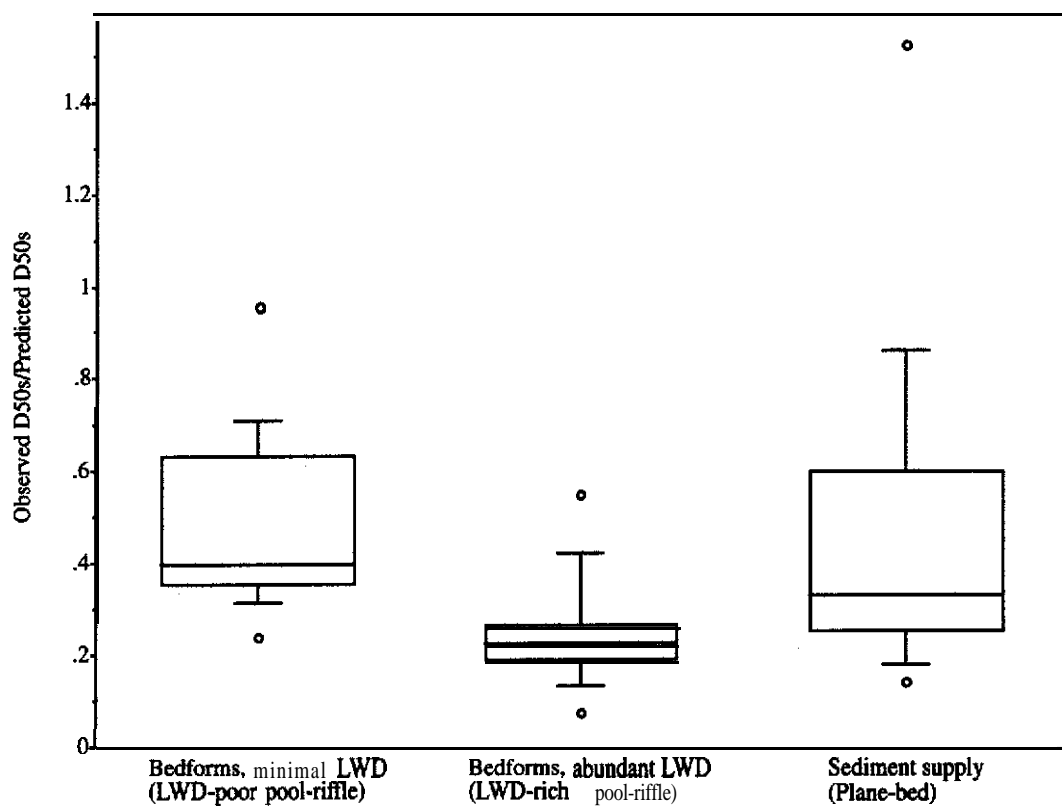


Figure 4.2 Empirical textural response ranges due to sediment supply, **bedforms** and minimal LWD, and **bedforms** and significant LWD. Line within each box plot represents the median value of the distribution, box ends are the inner and outer quartiles, whiskers are the inner and outer tenths, and circles **are** extrema. The sediment-impacted Lower Greens Creek is not included here..

The predicted D_{50s} is determined as $D_{50s} = \tau' / [(\rho_s - \rho)g\tau^* c_{50s}]$, where $\tau' = \tau_0 - \tau_w$; other grain size values are measured in the field. Equation (7) is defined as the response ratio. While this ratio is quite similar to the q^* formulation [i.e., (6)], it differs from q^* in that it expresses textural response to both sediment supply and hydraulic roughness. A channel's ability to accommodate increased sediment loads or hydraulic roughness via textural fining will be exhausted as surface median grain sizes approach that of the subsurface; that is, as (7) approaches a value of 1. Further increases in sediment supply or hydraulic roughness can only be accommodated by sediment deposition and channel aggradation.

Of the channel types investigated, LWD-rich channels show the strongest magnitude of textural fining (Fig. 4.1). As such, it was expected that they would have larger response ratios and thus the least capacity for further textural response (Buffington and Montgomery, 1992; Buffington, 1993). Figure 4.3 shows that increased textural fining (expressed as the ratio of observed-to-predicted D_{50s}) roughly corresponds with an increasing response ratio. LWD-rich pool-riffle channels tend to exhibit greater textural fining and larger response ratios than plane-bed channels (Fig. 4.3), however the zonation of textural response by channel type is less clear than that of Figure 3.15 due to a paucity of available D_{50ss} data. The significant overlap of response ratios amongst channel types should preclude any *a priori* association of response ratio and channel type. The trend of decreasing response ratio with increasing complexity of channel roughness does, however, indicate that the potential for sediment supply to influence surface textures should decline in channels with greater **bedform** and LWD roughness, in that there is progressively less capacity for further textural response. Hence, the component of sediment-supply-induced textural fining in channels with significant structural roughness must be relatively small.

The **bankfull** threshold model can also be used to assess channel condition in terms of sediment supply alone, provided that roughness effects on shear **stress** have been

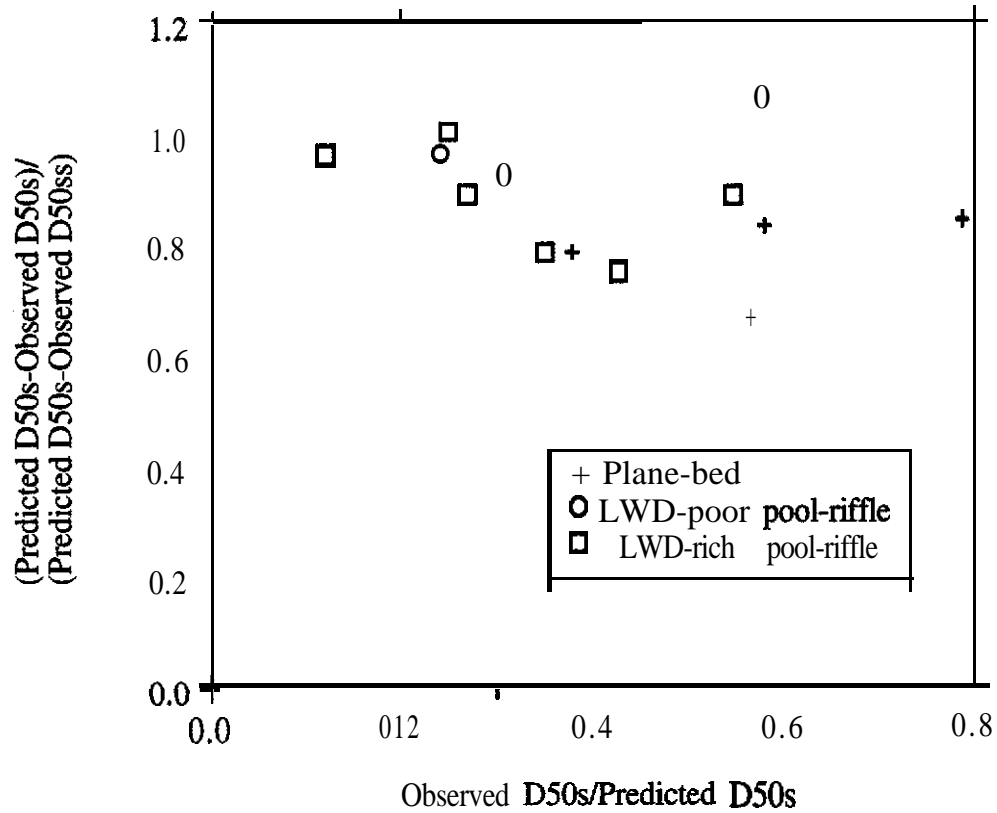


Figure 4.3 Textural fining relative to the **bankfull** threshold prediction of grain size (Observed D_{50s} / Predicted D_{50s}) versus response ratio $[(\text{Predicted } D_{50s} - \text{Observed } D_{50s}) / (\text{Predicted } D_{50s} - \text{Observed } D_{50ss})]$. Note that the predicted D_{50s} value is calculated as $D_{50s} = \tau' / [(\rho_s - \rho) g \tau' c_{50s}]$ using $\tau' = \tau_0 - \tau_w$. The sediment-impacted Alder Creek is not included here.

accounted for. Assessment of sediment loading is made by evaluating (7), with τ' established as per (5), subtracting any shear stress dissipation caused by hydraulic roughness elements other than grain roughness. However, prediction of τ' in forest channels is **difficult** due to the spatial complexity and irregularity of both **bedforms** and LWD, and is a subject for future research. The difficulty in accounting for roughness effects during channel assessment is recognized in the watershed analysis manual developed by the State of Washington (WFPB, 1993). Its authors recommend that when estimating sediment loading with the q^* technique (Dietrich et al., 1989), data should be collected in planar sections of channel away from roughness elements such as **bedforms** and LWD (WFPB, 1993). However, hydraulic roughness features have a reach-scale influence on surface textures and are not limited to local zones of response (i.e., Fig. 3.16). Furthermore, **the** full downstream extent of textural influence of an obstruction is uncertain. Velocity defects caused by much simpler flow obstructions can extend over downstream distances of several hundred obstruction-diameters (Grass, 1971). Without correction for roughness effects, q^* measurements in most forest gravel-bedded channels are suspect. Because Kinerson (1990) worked in channels with **bedform** and LWD roughness and chose sample sites in a fashion analogous to that recommended by WFPB (1993), some of his q^* **values** may also be affected by downstream persistence of energy dissipation and associated textural fining.

Once **channel** condition is established using (7), the empirical **findings** summarized by Figure 4.1 can be used to predict general trends of likely textural response to perturbations in sediment supply and hydraulic roughness. For example, channels with low response ratios will likely exhibit textural fining as a result of aquatic enhancement projects that add in-stream debris. Alternatively, textural coarsening is predicted for **LWD**-rich pool-riffle channels that are depleted of in-stream debris as a consequence of such

factors as debris flow scour, management stream cleaning (Meehan et al., 1969; Bryant, 1983), or recruitment decline following riparian harvest (Murphy and Koski, 1989). Channels directly receiving road drainage and associated sediment loads will exhibit textural **fining** if the response capacity is available; if not, deposition and channel aggradation is likely.

Textural response may, however, be more complicated than indicated by the above simple predictions. Changes in the caliber of supplied sediment will affect the assessment of channel condition. For example, if for some reason the caliber of the sediment load decreases, but the **volume** supplied does not change, then the **bedload** (and hence subsurface) grain size distribution will **fine**, increasing the response ratio and raising the channel capacity for surface textural **fining**. LWD can also cause complex textural responses. Because of the influence of woody debris on forest channel morphology (i.e., Fig. 3.13), changes in LWD loading may alter **bedform** configuration and roughness, which may intensify or counteract any LWD-induced textural response depending on the specific circumstances. To a large degree woody debris must also control **bedload** (and hence subsurface) grain sizes by influencing the magnitude of basal shear stress available. For example, addition of LWD and consequent shear **stress** dissipation will result in a reach-average decline in **bedload** (and subsurface) grain **size** caliber, extending the lower limit of potential **textural** response of the surface by decreasing D_{50ss} . Concomitant declines in surface grain size may, however, offset any potential increase in channel response ratio. Increased roughness due to the addition of LWD will also result in decreased velocity and water surface slope, causing increases in either water depth or width or both (Lisle, 1986a); changes in hydraulic variables such as this can alter τ_0 . The point of these examples is to illustrate that textural response may not always follow a simple, predictable path.

In addition to predicting **likely** response trends, more specific predictions can also be made from the field data. Although there is considerable scatter, textural **fining** expressed as the ratio of observed-to-predicted **D_{50s}** generally declines with increasing LWD loading (Fig. 4.4). Furthermore, for a given LWD loading the degree of textural **fining** depends on channel shear stress (Fig. 4.4); higher shear stresses generally correspond with greater textural fining (i.e., lower ratio of observed-to-predicted **D_{50s}**). This is also evidenced in Figure 4.1 by the increase in range of textural fining observed in pool-riffle channels at greater shear stresses. Because larger channel shear stresses also mean greater velocities, identically placed obstructions will cause greater form drag, and hence greater textural fining, in higher-velocity channels. Textural response predictions made from Figure 4.4 should be viewed as estimates only, as the figure does not explicitly include **bedform** dimensions and other physical attributes of LWD which together control macro-scale form **drag** and textural fining. Form drag, and hence textural fining, should be correlated with: 1) **bedform** amplitude and wavelength; and 2) LWD size, orientation, position within the flow column, and abundance. Only the later is explicitly represented in Figure 4.4. Furthermore, sediment supply effects, while arguably small in these channels, are also not explicitly accounted for in Figure 4.4.

Specific magnitudes of textural response to changes in sediment supply are also predictable when examined within the threshold model framework. The magnitude of textural **fining** relative to model predictions (i.e., Predicted **D_{50s}**-Observed **D_{50s}**) is a power function of sediment loading (Fig. 4.5). In contrast, textural fining expressed as the ratio of observed-to-predicted **D_{50s}** is not a unique function of sediment supply (Fig. 4.6); rather, it is apparently dependent on the ratio of τ'/τ_{c50s} , with the rate of textural fining less rapid for larger values of this shear stress ratio. Like the observed-to-predicted ratio of **D_{50s}**, q^* is a relative measure not singularly related to sediment supply (Fig. 4.7). While

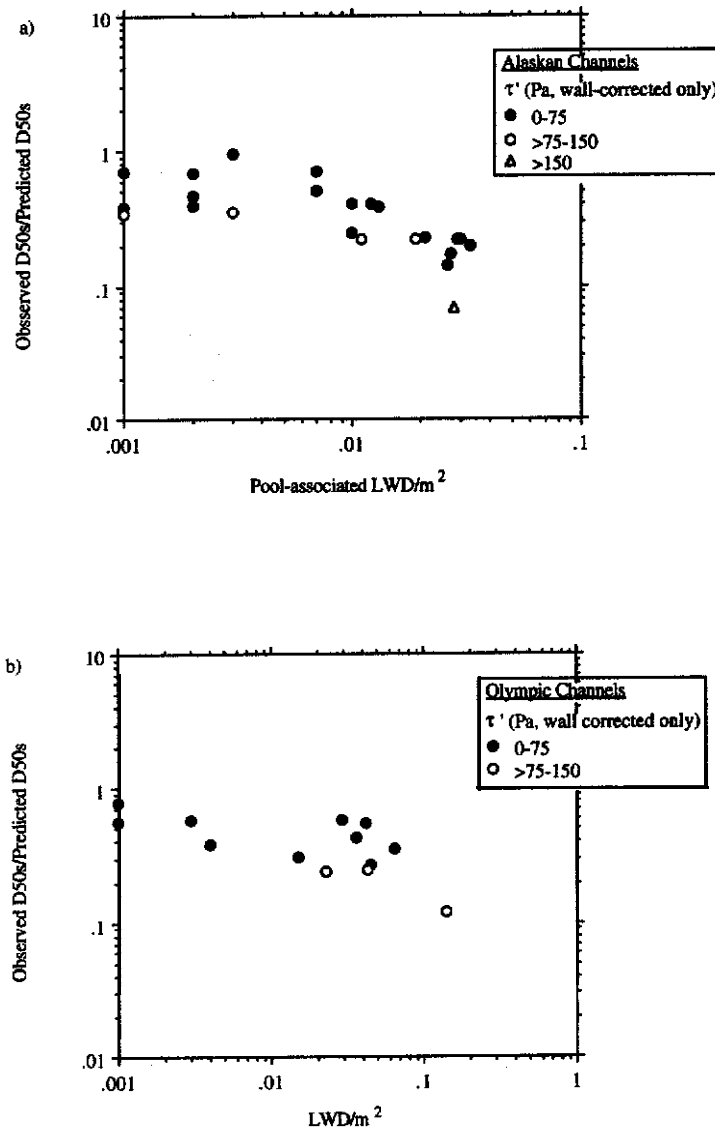


Figure 4.4 **Textural fining** as a function of LWD loading in the a) Alaskan and b) Olympic channels. Textural **fining** is expressed as deviation from unity for the ratio of **observed-to-predicted D_{50} s**, and LWD loading is **represented** by pool-associated pieces/m* and total **pieces/m²** for the Alaskan and Olympic sites, respectively. The sediment-impacted Alder Creek and Lower **Greens** Creek are not included here.

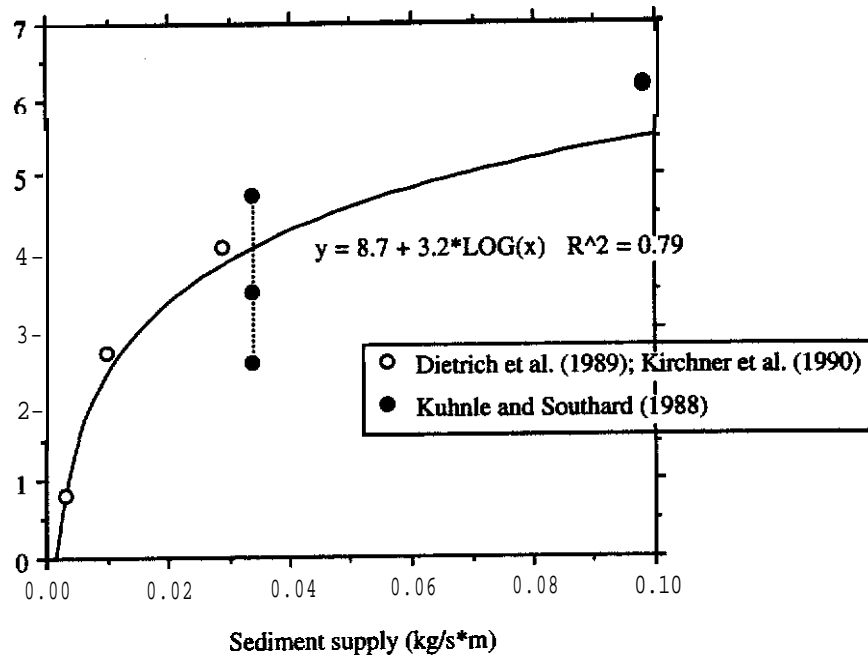


Figure 4.5 Sediment supply ($\text{kg/m}\cdot\text{s}$) versus magnitude of textural **fining** relative to the **bankfull** threshold channel prediction (Predicted D_{50s} -Observed D_{50s}). D_{50s} is predicted based on $\tau^*_{c50s}=0.032$.

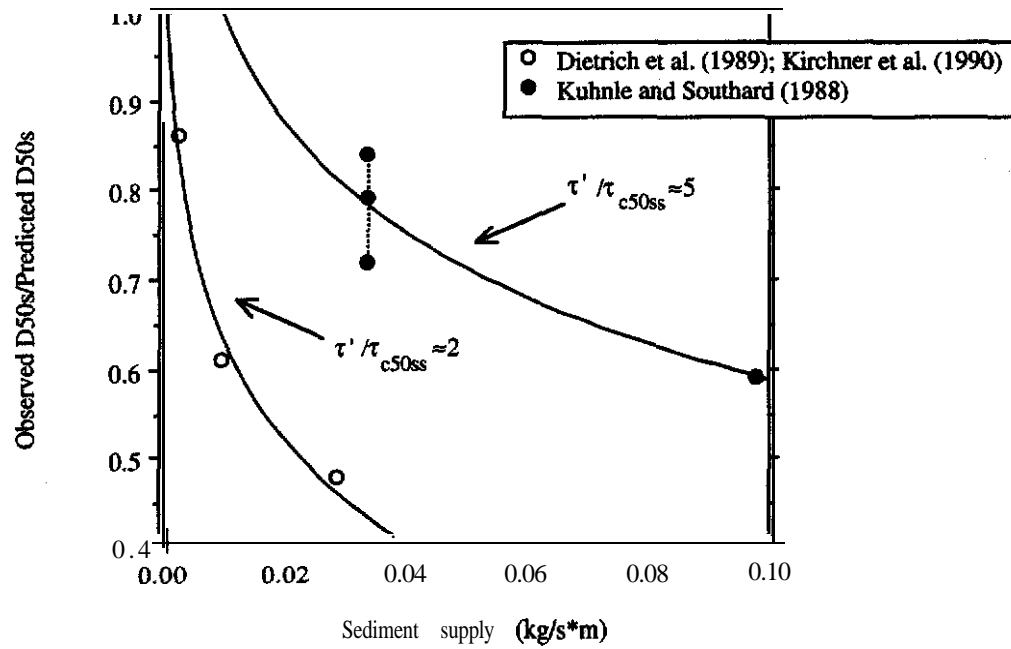


Figure 4.6 Sediment supply (kg/m@ versus relative textural fining(Observed D&Predicted D_{50s}). D_{50s} is predicted based on $\tau^*_{c50s}=0.032$.

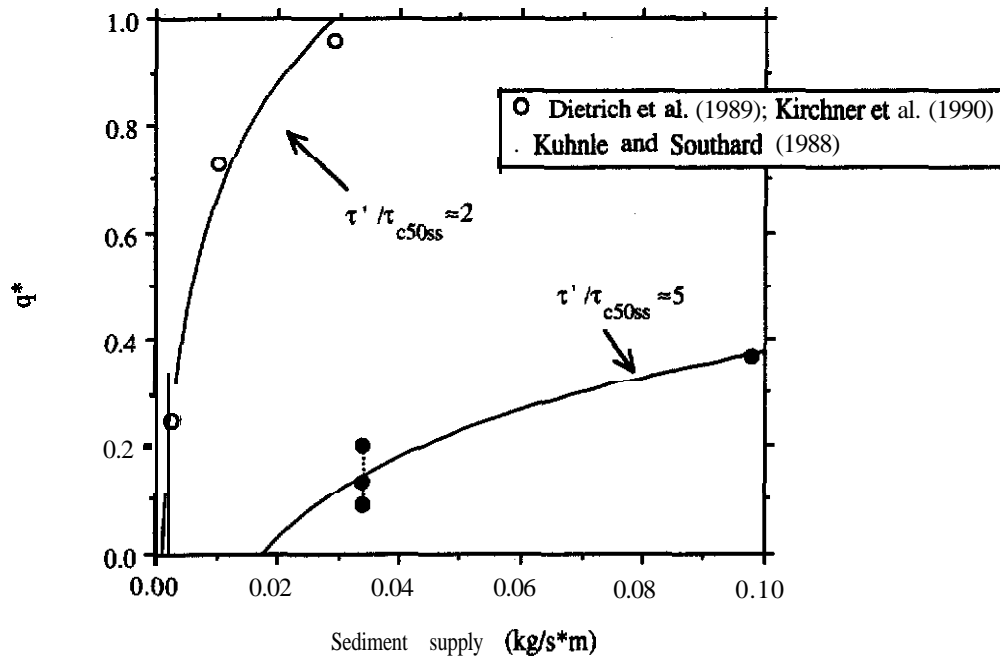


Figure 4.7 Sediment supply ($\text{kg/m}\cdot\text{s}$) versus q^* , based on $\tau^*_{c50s} = 0.032$.

q^* can be used to infer qualitative degrees of **sediment** loading, magnitudes of textural fining measured within the **bankfull** threshold framework allow assessment of specific sediment loading (Fig. 4.5). The uniqueness of this relationship is, however, quite sensitive to the τ^*_{c50s} value used. Larger τ^*_{c50s} values produce families of curves for which the rate of textural **fining** with increasing sediment supply is inversely dependent on τ/τ_{c50ss} . Smaller τ^*_{c50s} values result in a direct dependence of **fining** rate on τ/τ_{c50ss} . Variation of τ^*_{c50s} does not affect the relative dependence on τ/τ_{c50ss} shown in Figures 4.6 and 4.1.

TEXTURAL RESPONSE AND SALMONID HABITAT

Surface textures have direct implications for availability of **salmonid** spawning habitat. While channel characteristics such as temperature, depth, velocity, gravel “embeddedness” (e.g., Peterson et al., 1992), substrate content of fines, and intra-gravel flow and upwelling are believed to affect selection of spawning sites, perhaps the most important characteristic is the physical size of the gravel in **which** an adult salmon can excavate a **redd**. Typical median grain sizes of spawning gravels used by various salmonids as reported by Kondolf and Wohlan (1993) are overlain on the empirical findings of the threshold channel model in Figure 4.8. Chinook salmon (*Oncorhynchus tshawytscha*) and chum salmon (*O. keta*) are tolerant of a broad range of spawning gravel sizes, while pink salmon (*O. gorbuscha*) and brook trout (*Salvelinus fontinalis*) are restricted to a very narrow range; spawning gravels preferred by the remaining salmonids have a total variance in median grain size of about 15 mm. Coupled with the empirical findings of the **bankfull** threshold model, these preferred spawning grain sizes allow examination of the geomorphic controls on species-specific spawning habitat availability. The level of examination afforded by this coupling is quite coarse, however, as the

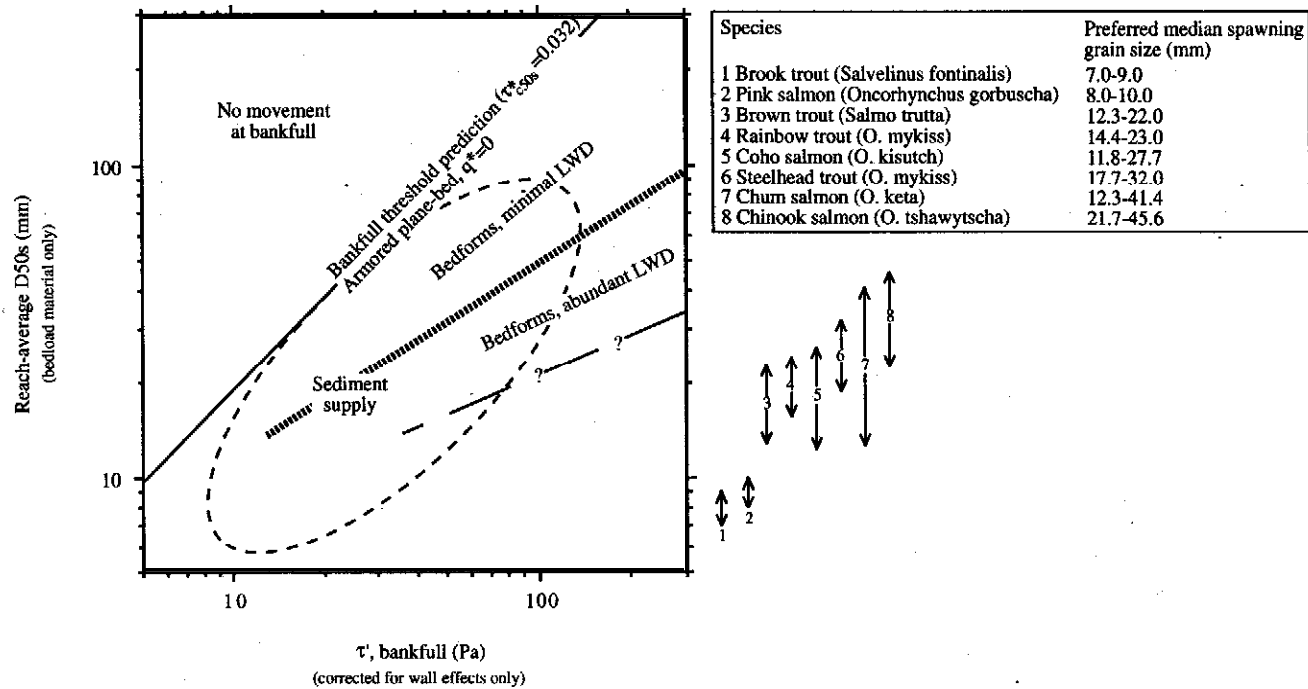


Figure 4.8 Comparison of the empirical results of the bankfull threshold model and median spawning grain sizes used by salmonids. Spawning gravel ranges represent the 25th and 75th percentiles of the median grain size distributions reported in Kondolf and Wolman's (1993) Figure 7. It is cautioned that these ranges should be viewed as estimates only, as Kondolf and Wolman's (1993) synthesis combines disparate and potentially erroneous data sets. Their data include both pre- and post-spawned gravels, grain size distributions of which are typically quite different (Kondolf et al., 1993; Montgomery et al., in review). Some sources used by Kondolf and Wolman (1993) ignored the larger grain sizes present in spawning gravels, skewing actual grain size distributions toward finer sizes. Most importantly, substrate samples in fisheries studies typically combine both surface and subsurface material and only measure a small volume of sediment; as such, grain size distributions may be erroneous (Church et al., 1987) and of uncertain application to the threshold model's prediction of D_{50s} . There is a need for more accurate and standardized characterization of preferred pre-spawning gravel sizes used for salmonid spawning.

empirical results of the current study represent reach-average D_{50s} values which unfortunately give no information on the actual variability and abundance of suitable spawning patches **within** a reach. Nevertheless, it is a useful starting point. Figure 4.8 shows that availability of preferred spawning grain sizes is significantly enhanced by textural response to sediment supply and hydraulic roughness. For example, preferred spawning gravel sizes for **coho** salmon (0. *kisutch*) in fully armored plane-bed channels (i.e., channels not exhibiting textural fining) only occur for **bankfull** shear stresses ranging from about 7-14 Pa (Fig. 4.8). However, as a result of textural fining, spawning sizes preferred by **coho** have the potential to occur in a variety of different channel types and over a greater range of **bankfull** shear stresses (7-146 Pa, Fig. 4.8). Consequently, textural response can significantly increase spawning habitat availability for a given **salmonid** species.

Figure 4.8 can also be used to examine the potential impacts of textural response on availability of **species-specific** spawning gravels. Textural response to changes in sediment supply or hydraulic roughness that extend beyond **the** range of median spawning sizes preferred by a particular species may cause them to abandon such reaches as spawning sites. For example, brown trout (*Salmo trutta*), which prefer relatively small spawning grain sizes, may abandon a LWD-rich pool-riffle channel as a spawning site if it coarsens significantly in response to a depleted wood supply. Wood loss may further compound impacts on a **salmonid** population by decreasing pool frequency and **thus** availability of potential rearing habitat (Montgomery et al., in press).

Forest channels with abundant LWD are widely recognized for the availability of potential spawning and rearing habitat that they offer (Everest et al., 1987; Sullivan et al., 1987; Bisson et al., 1987). The main significance of LWD is the channel “complexity” that it creates; that is, the obstruction-forced spatial variability of channel hydraulics, morphology, and grain **size** that satisfy some of the requirements of different **salmonid**

species and their life-stages. The increasing complexity and spatial variability of surface textures with greater wood loading is clearly noted in the current analysis. **Ironically** the LWD-rich pool-riffle channels may be the most valuable for salmonid usage and potentially the most sensitive to increased sediment supply or hydraulic roughness, in that they commonly have high response ratios (Fig. 4.3) and thus a small capacity for further textural response.

CONCLUSION

The **bankfull** threshold model provides a useful framework for examining textural response to sediment supply and other hydraulic roughness elements in gravel-bedded streams. Reach-average surface textures exhibit systematic **fining** in response to both of these factors. While sediment loading and hydraulic roughness **are** both **first-order** controls on reach-average median surface grain size, the infrequent nature of significant sediment input to forest channels likely causes sediment supply effects to be subordinate to the pervasive influence of LWD and **bedforms** in forest pool-riffle channels.

The interpretation of empirical results presented here and the assessment of relative magnitudes of textural influence caused by sediment supply and hydraulic roughness features of natural channels is preliminary and warrants further investigation. Future work will pursue this subject **through** rigorous partitioning of **bedform** and LWD shear stresses using theoretical boundary layer calculations. Theoretical calculations will be compared **with** field measurements of channel roughness. Once shear stress dissipation due to **in-**channel roughness features is accounted for, sediment supply effects on reach-average surface textures can be determined independently and compared with conclusions made in **the** current analysis.

Textural response to sediment supply and hydraulic roughness occurs on both a reach and local scale, and further investigation of the latter is recommended. In particular, textural patch dynamics should be examined in order to better understand channel hydraulics and sediment transport at a **subreach** scale. When and how is sediment transported within and between patches and how do seasonal variations in shear stress and surface texture affect this? A better understanding of surface textures at a **subreach** scale would be valuable for assessing and predicting geomorphic controls on availability of spawning gravels for salmonids and other fishes.

NOTATION

C_D, C_L	drag, lift coefficient
D_{50}, D_{84}, D_i etc.	grain size for which 50% , 84%, $i\%$, etc. of the grains are finer
$D_{50s}, D_{50ss}, D_{50m}$	median grain size of the surface material, subsurface material, laboratory mixture
D_{gs}	geometric mean grain size of the surface material
D^*	Dietrich's (1982) dimensionless grain size
D_i^*	Kirchner et al.'s (1990) dimensionless grain size, D_i/z_0
D_{maxs}, D_{maxss}	largest surface, subsurface grain size
D_n	nominal grain size
D_{sus}	maximum suspendable grain size at bankfull flow
e, e_i^*	Kirchner et al.'s (1990) dimensional and dimensionless gram exposure, e_i/D_i
f_i	fraction of grain size distribution comprised by D_i
g	gravitational constant
h	depth
h_c	critical depth for incipient motion
k_s	boundary roughness length scale (equivalent Nikuradse (1933) sand grain roughness)
m	mixed grain size
n_0, n_g	total, grain Manning (1891) roughness coefficient
p, p_i^*	Kirchner et al.'s (1990) dimensional and dimensionless grain projection, p_i/D_i
Q, Q_s	total volumetric fluid discharge, that over the bed only (Meyer-Peter and Müller , 1948)
q^*	Dietrich et al.'s (1989) dimensionless bedload transport rate
Re^*_c, Re^*_{ci}	critical grain/boundary Reynolds number for D_{50}, D_i

S	water surface/bed surface slope in m/m
T	texture
u	velocity
u	uniform grain size
u*	shear velocity
v*	Lisle and Hilton's (1992) sediment supply parameter
W	width
w _s	grain fall velocity
w*	dimensionless grain fall velocity
z	height above the bed
z ₀	total roughness length scale
z*	Kirchner et al.'s (1990) dimensionless height above the bed, z/D_i
α	empirical coefficient
β	empirical exponent
γ	specific weight of fluid
θ	bed surface slope in degrees
κ	von Kármán's constant
ν	kinematic viscosity
ρ, ρ _s	fluid, sediment density
σ _{gs} , σ _{gss} , σ _{gm}	sorting coefficient Folk's (1974) graphic standard deviation] of the surface material, subsurface material. laboratory mixture
τ ₀	total bankfull boundary shear stress
τ'	effective bankfull boundary shear stress
τ _f	component of τ ₀ expended on bedform drag
τ _g	component of τ ₀ expended on skin friction and form drag of bed surface grains
τ _l	component of τ ₀ expended on LWD (see text for mechanisms of energy dissipation)
τ _w	component of τ ₀ dissipated by sidewall effects
τ _c	critical shear stress (value for incipient motion)

τ_{c_i}, τ_{c50s}	τ_c of $D_i, D50s$
τ_{c_q50s}	τ_c of $D50s$ based on empirical competence equations determined from coupled bedload sampling and shear stress measurement
$\tau_{c_r50}, \tau_{c_r50m}$	τ_c of $D50, D50m$ for a specified reference bedload transport rate
τ_{c_v50m}	τ_c of $D50m$ based on visual observation of incipient motion
τ^*	dimensionless shear stress
τ^*_c	dimensionless critical shear stress (value for incipient motion)
$\tau^*_{c_i}, \tau^*_{c50}, \tau^*_{c50s}, \tau^*_{c50ss}, \tau^*_{c50m}$	τ^*_c of $D_i, D50, D50s, D50ss, D50m$
$\tau^*_{c_q}$	τ^*_c based on empirical competence equations determined from coupled bedload sampling and shear stress measurement
$\tau^*_{c_{qi}}, \tau^*_{c_{q50}}, \tau^*_{c_{q50s}}, \tau^*_{c_{q50ss}}$	τ^*_c of $D_i, D50, D50s, D50ss$ based on empirical competence equations determined from coupled bedload sampling and shear stress measurement
$\tau^*_{c_{ri}}, \tau^*_{c_{r50}}, \tau^*_{c_{r50s}}, \tau^*_{c_{r50m}}$	τ^*_c of $D_i, D50, D50s, D50m$ for a specified reference bedload transport rate
$\tau^*_{c_{vi}}, \tau^*_{c_{v50}}, \tau^*_{c_{v50m}}$	τ^*_c of $D_i, D50, D50m$ based on visual observation of incipient motion
ϕ	log ₂ gram size
'S16, ϕ_{84} , etc.	grain sizes for which 16%, 84% , etc. of the grains are finer
Φ	intergranular friction angle

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APPENDIX I: TABLE 1.1 NOTES

- I Using a dimensionless **bedload** transport formulation and a subset of Milhous' (1973) data, Parker and Klingeman (1982) extrapolated fractional **bedload** transport rates to a low reference **value** assumed representative of initial motion and calculated corresponding $\tau^*_{c_{ri}}$ values from the Shields equation. These values were in turn expressed as a function of D_i/D_{50s} . Only **bedload** transport data from armor-breaching events in the winter of 1971 were used (Parker and Klingeman, 1982; Komar, 1987a). $\tau^*_{c_{r50s}}$ is simply the value of this function with $D_i/D_{50s}=1$. The exponent of the Parker and Klingeman (1982) $\tau^*_{c_{ri}}$ function was estimated by JMB from their Fig. 3. Parker and Klingeman (1982) report $D_{50s} \approx 54$ mm [pg. 1411 and Table 1, Parker and Klingeman (1982)], however Milhous (1973) indicates that D_{50s} was 60-63 mm in 1971 [Tables 2 and 3, Milhous (1973)]. Using Milhous' (1973) median surface grain sizes and Parker and Klingeman's (1982) $\tau^*_{c_{ri}}$ function yields $\tau^*_{c_{50s}} = 0.03$ to 0.032. σ_{gs} was calculated by JMB from data presented in Parker and Klingeman's (1982) Table 1.
- 2 Using Parker and Klingeman's (1982) technique (note I), $\tau^*_{c_{ri}}$ values were determined for Milhous' (1973) data and expressed as a function of the ratio D_i/D_{50ss} (Wilcock and Southard, 1988). $\tau^*_{c_{r50s}}$ was calculated by JMB from this function [Table 6, Wilcock and Southard (1988)], taking $D_i = D_{50s} = 54$ mm (Parker and Klingeman, 1982) and $D_{50ss} = 19.5$ mm [Table 1, Wilcock and Southard (1988)]; although it is not clear from Wilcock (1987), I assume that in following Parker and Klingeman's (1982) analysis Wilcock used the Oak Creek grain size data presented by them [Table 1, Parker and Klingeman, (1982)]. Wilcock's (1987) flume experiments were corrected for form drag and sidewall effects, but it is uncertain if Wilcock and Southard (1988) applied similar

corrections to the other data sources that they used [i.e., that of **Milhous (1973)**]. σ_{gs} is that reported for Parker and Klingeman (1982).

- 3 $\tau^*_{c_{Ti}}$ values were determined using a simplified version of Parker and Klingeman's (1982) technique (note I) and regressed as a function of the ratio D_i/D_{50s} (Ashworth and Ferguson, 1989). $\tau^*_{c_{150s}}$ values were determined by JMB from these functions [eqns (8a-c), **Ashworth and Ferguson (1989)**] with $D_i/D_{50s}=1$. D_{50s} values are averages of those reported in **Ashworth and Ferguson's (1989) Table 1**. In order to correct for form drag and other types of shear stress dissipation not accounted for by a simple **depth-slope** representation of critical shear stress, **Ashworth and Ferguson (1989)** used local point **measures** of shear stress to calculate τ_{c_i} . Nevertheless, their local estimates of boundary shear stress likely overestimate the effective bed shear stress, as they calculated boundary shear stress from the **full velocity profile**, rather than just over **near-bed** heights [see discussion of segmented velocity profiles in **Middleton and Southard (1984)** and **Smith and McLean (1977)**]. Their local velocity measures do, however, implicitly account for sidewall effects.
- 4 Parker's (1990) study simply re-visits the Parker and Klingeman (1982) study and expresses $\tau^*_{c_{Ti}}$ in terms of the ratio D_i/D_{gs} , where D_{gs} is the geometric mean surface size defined as $\ln D_{gs} = \sum f_i \ln D_i$ (Parker, 1990); f_i is the fraction of the weight distribution comprised by D_i . $\tau^*_{c_{Ti}}$ was calculated by JMB using $D_{gs}=45.2$ mm [pg. 428, **Parker (1990)**] and $D_i=D_{50s}=55$ mm [Table 1, **Parker (1990)**]; note that these values are based on a grain size distribution for which the sand fraction was removed (Parker, 1990). σ_{gs} was calculated by JMB from data presented in Parker's (1990) Table 1.

5 $\tau^*_{c_{q50s}}$ was calculated by JMB from Andrews' (1983) eqn (2) using D_{50s} and D_{50ss} values reported by Andrews and Erman (1986). Although eqn (2) was developed from other data (Andrews, 1983) it shows reasonable agreement with the **bedload transport** data presented by Andrews and Erman (1986). Andrews' (1983) development of eqn (2) is, however, quite contorted. Using Shields' (1936) equation, dimensionless critical shear stresses were calculated for the geometric mean diameter of the largest grain size fraction **sampled** during **bedload** transport events in three North American rivers (Andrews, 1983). Critical shear stress was estimated from a depth-slope product employing a reach-average water surface slope and the flow depth over the zone of maximum **bedload** transport. The largest mobile particles for **all** of the sampled events in a given river were then grouped by size class and the average calculated critical shear stress was determined for each size class, $\bar{\tau}^*_{c_{qi}}$. These values from all three rivers were then regressed against the ratio D_i/D_{50ss} , yielding Andrews' (1983) equation (2). σ_{gs} was calculated by JMB from grain sizes estimated from Andrews and Erman's (1986) Fig. 4.

6 Using **bedload** transport data from Milhous (1973), Carling (1983), and Hammond et al. (1984), Komar (1987a) developed empirical competence equations for each study site, expressing competence as a power-law function between shear stress and the largest mobile grain size sampled during **bedload** events [Table 1, Komar (1987a)]. Each competence equation was re-written in terms of a power-law function for dimensionless critical shear stress of the form $\tau^*_{c_{qi}} = \alpha(D_i/D_{50})^\beta$ [similar to that used by Parker et al. (1982) and Andrews (1983)]. The Milhous $\tau^*_{c_{qi}}$ equation was determined through algebraic manipulation of the corresponding competence equation, taking D_{50} as the subsurface median grain size [pg. 207, Komar (1987a)]. Noting that the Milhous

competence **equation crossed the** Shields curve [us defined by Miller et al. (1977)] at $D_i \approx D_{50ss} \equiv D_{50}$, Komar (1987a) determined D_{50} values for the Carling and Hammond et al. $\tau^*_{c_{qi}}$ equations from the respective cross-over values Of D_i [Fig. 3, Komar (1987a)]. Based on analogy with the Milhous data I assume that the Carling and Hammond et al. cross-over values correspond with D_{50ss} , making Komar's (1987a) reported $\tau^*_{c_{qi}}$ equations functions of D_i/D_{50ss} ; however, cross-over points for Day's (1980b) competence functions apparently correspond with his reported D_{50m} values [Fig. 2, Komar (1987a)].

Using the empiricism that $D_i/D_{50} \approx 1$ at the cross-over, a values for the Carling and Hammond et al. $\tau^*_{c_{qi}}$ equations were fixed from cross-over points with the Miller et al. (1977) Shields curve [Fig. 4, Komar (1987a)], leaving β to be back-calculated. Komar (1987a) found that the resultant Carling $\tau^*_{c_{qi}}$ equation appeared to describe Milhous' data quite well, so he used it to represent Milhous' data, abandoning the algebraically defined Milhous $\tau^*_{c_{qi}}$ equation (cf. pg. 207, Fig. 5, and Table 1 of Komar (1987a)). Rejecting this unsound rationale, I have maintained the original algebraically defined Milhous $\tau^*_{c_{qi}}$ equation in Table 1.1.

JMB calculated $\tau^*_{c_{q50s}}$ values from these "derived" $\tau^*_{c_{qi}}$ equations [Table 1, Komar (1987a)], using values of $D_i = D_{50s}$ and $D_{50} = D_{50ss}$ culled from other sources (see following notes).

7 $\tau^*_{c_{q50s}}$ was calculated by JMB from the originally defined Milhous equation, $\tau^*_{c_{qi}} = 0.044(D_i/D_{50})^{-0.43}$ [pg. 207, Komar (1987a)], using Komar's (1987a) reported values of $D_{50} = D_{50ss} = 20$ mm (Table 1) and $D_i = D_{50s} = 60$ mm (pg. 207). σ_{gs} was based on D_{90s} and D_{10s} from Milhous' (1973) Table 3.

- 8 The Carling $\tau^*_{c_{qi}}$ expression [Komar (1987a), Table 1] was based on a subset of Carling's (1983) **bedload** transport data; only data from Great Eggeshope Beck were used. JMB calculated $\tau^*_{c_{q50s}}$ from this expression using the cross-over **value** of $D_{50}=D_{50ss}\approx 20$ mm [Komar (1987a), Table 1] and $D_i=D_{50s}=62$ mm [Komar and Carling (1991), Table 1]. This D_{50s} value is derived from the framework gravel distribution, which is observationally very similar to the censored (i.e., armored) surface layer distribution (Carling and Reader, 1982).
- 9 $\tau^*_{c_{q50s}}$ was calculated by JMB from the Hammond et al. $\tau^*_{c_{qi}}$ equation [Komar (1987a), Table 1] using Komar's (1987a) reported value of $D_{50}=D_{50ss}=7.5$ mm (Table 1) and $D_i=D_{50s}=21$ mm [estimated by **JMB** from the Fig. 3 TV data of Hammond et al. (1984)].
- IO JMB calculated $\tau_{c_{q50s}}$ from the Fahnestock (1963) competence equation reported by Komar (1987b, Table 1), and in turn used this **value** to determine $\tau^*_{c_{q50s}}$ from the Shields equation. For these calculations D_{50s} was determined from the composite White River grain size data [Fahnestock (1963), Table 2].
- II The data sets differ from those used by Komar (1987a) in that more data from Great Eggeshope Beck were included and, as with the Parker and Klingeman (1982) study, only the subset of **Milhous'** (1973) data corresponding with armor-breaching events was analyzed (Komar and Carhng, 1991). $\tau^*_{c_{q50s}}$ **values** were calculated by **JMB** from relevant equations [Komar and Carhng (199 1), Fig. 9] and gram sizes [Komar and Carling (1991). Table 1]. Although the caption for Komar and Carling's (199 1) Fig. 9 indicates that the Great Eggeshope Beck $\tau^*_{c_{qi}}$ equation is expressed as a function of

median subsurface grain size, the **normalizing** grain size used by the authors (62 mm) is that of the framework gravel [pg. 498, Komar and Carling (1991)], which is equivalent to the censored (i.e., armored) surface size (**Carling** and Reader, 1982); Komar and Carling's (1991) Table 1 also indicates that **the** 62 mm median framework size is a surface **value analogous** to that of the surface material in Oak **Creek**. Despite the caption for Komar and Carling's (1991) Fig. 9, only the Oak Creek $\tau^*_{c_{qi}}$ equation is expressed as a function of D_{50ss} ; the Great **Eggleshope** Beck $\tau^*_{c_{qi}}$ equation is a function of D_{50s} .

12 $\tau^*_{c_{q50s}}$ was based on Milhous' (1973) Fig. 21 which is a plot of **the** maximum mobile grain size sampled in a pit **bedload** trap versus τ/γ ; $\tau^*_{c_{q50s}}$ was estimated by JMB from contoured Shields stresses shown on this plot. Virtually **the** full range of grain sizes sampled during Milhous' (1973) experiments share a common minimum $\tau^*_{c_q}$ value of 0.025, **re-enforcing** the concept of "equal mobility" (Parker et al., 1982). Grain sizes plotted in Milhous' (1973) Fig. 21 are nominal diameters calculated from weights of **the** largest particle captured by the trap. Cui and Komar (1984) argue that the nominal diameter of a grain is on average equivalent to the grain's intermediate diameter; this similarity of measures is assumed here. τ_c was calculated from the maximum **depth-slope** product during a **bedload** transport event. σ_{gs} was based on D_{90s} and D_{10s} from Milhous' (1973) Table 3.

13 Carling (1983) expressed incipient motion in terms of a power function between total boundary shear stress (calculated as a depth-slope product) and the average size of the five largest **bedload** particles sampled during an event. Similarly, Shields stress was expressed as a power function of Re^* ($=u_*D_i/\nu$) (Carling, 1983). JMB calculated $\tau^*_{c_{q50s}}$ from these expressions and other reported data. For example, **the** following

procedure was used for Great Eggeshope Beck: taking D_{50s} as the median grain size of the framework distribution [Table 1, Komar and **Carling** (1991)], $\tau_{c_{q50s}}$ was determined from Carling's (1983) equation (7); with this value, u^*_c and in turn Re^*_c was estimated, allowing calculation of $\tau^*_{c_{q50s}}$ from Carling's (1983) equation (9). In calculating Re^*_c it was assumed that $\nu=10^{-6}$ m²/s. $\tau^*_{c_{q50s}}$ for Carl Beck was estimated in a similar fashion using appropriate equations for Carl Beck and the mean framework gravel **size reported** by Carling and Reader (1982).

- 14 $\tau^*_{c_{q50s}}$ values are fit from a semi-theoretical critical discharge formulation employing Bathurst's (1987a) **bedload** transport data which is expressed in terms of the average maximum grain size mobilized during a given peak discharge (Ferguson, 1994). Ferguson's (1994) formulation combines an Andrews-type (1982) equation (assuming conditions of near equal mobility) with the Schoklitsch (1962) equation. Form drag and sidewall corrections are not explicitly considered, but may be indirectly accounted for to some degree by the Thompson and Campbell (1979) roughness empiricism used by Ferguson (1994); this empiricism, however, is likely only representative of the toughness conditions examined by Thompson and Campbell (1979).
- 15 Using empirically determined values in a theoretical critical shear stress formulation similar to that of White's (1940), Kalinske (1947) argues that $\tau_c=4D$ for uniform, **sand**-sized grains with $Re^*_c>3.5$; this equality is expressed in English units. $\tau^*_{c_{50s}}$ was calculated by **JMB** by re-writing Kalinske's (1947) competence expression in terms of the Shields equation.
- 16 **Çeçen** and Bayazit (1973) examined transport rates and grain size distributions of **bedload** material in an armored channel typical of natural, mountain streams. Equality of

armor and **bedload** grain **size** distributions was used to define incipient motion of the bed surface. The corresponding critical shear stress was found to equal that required for incipient motion of D_{50s} according to **Egiazaroff's (1965)** critical shear stress formulation (**Çeçen** and Bayazit, 1973).

17 τ^*_{c50s} was based on a theoretical critical shear stress formulation (Kirchner et al., 1990) employing friction angle and grain protrusion **measurements** made from **flume-**worked heterogeneous bed surfaces. Grain mobility here is for that of particles placed on a bed surface. τ^*_{c50s} values are calculated in the absence of form drag and sidewall effects. The specific τ^*_{c50s} value reported here was read from Kirchner and others' (1990) Fig. 18 for $D/K_{50}=1$ and $n=10$.

18 τ^*_{c50s} was determined from Kirchner et al.'s (1990) theoretical critical shear stress formulation employing friction angle **measurements** made from bed surfaces of a natural pool-riffle stream (**Buffington** et al., 1992). Grain mobility here is for that of particles placed on a bed surface. τ^*_{c50s} **values** are calculated in the absence of form drag and sidewall effects. The specific τ^*_{c50s} value reported here was read **from** Buffington and others' (1992) Fig. 13 for $D/K_{50}=1$ and $n=0.1$.

19 Using a simple "slab" shear model Jiang and Haff (1993) simulated particle motion of a heterogeneous bed surface, accounting for individual relative **grain** velocities, intergranular friction, and grain-to-grain collisions. Reported τ^*_{c50s} **values** bracket the calculated threshold of "continuous" motion, defined as one or more particles moving at all times (Jiang and Haff, 1993) during a simulation. **Bedform** drag and sidewall effects were not present in the simulations.

20 Using his own experiments and data reported by Casey (1935), Kramer (1925), USWES (1935), and Gilbert (1914), Shields (1936) calculated $\tau^*_{c_{r50m}}$ values for each laboratory sediment mixture using a reference critical shear stress corresponding to an extrapolated near-zero **bedload** transport rate of the mixture. Shear stresses were corrected for sidewall effects in Shields' (1936) experiments, but it is uncertain if such corrections were made for the other data sources used by Shields (1936). Some $\tau^*_{c_{r50m}}$ and Re^*_c values were read from Tison's (1953) Table II, but most were estimated by **JMB** from the Shields curve presented in Rouse's comments to Chang (1939). D_{16m} and D_{84m} values used to calculate σ_{gm} were estimated from Shields' (1936) Fig. 16. While Shields (1936) reports D_{50m} values used in his experiments, it is unclear which values correspond with a given point on the Shields curve. As such, assignment of D_{50m} values in Table 1 is based on a sensible match of grain size with reported $\tau^*_{c_{r50m}}$ and Re^*_c pairs for a particular sediment type.

21 D_{50m} values used in Casey's (1935) experiments were 0.85 mm, 1.23 mm, and 2.44 mm (Shields, 1936). However, assignment of these values to reported $\tau^*_{c_{r50m}}$ and Re^*_c pairs is uncertain. Shields (1936) chose D_{50m} values for his granitic grain experiments to mimic those of Casey (1935). If similarity of grain size distributions is also assumed, then Casey's (1935) experiments employed near-uniform sizes [$\sigma_{gm} \approx 0.23$ for Shields' (1936) granitic grains]. Other details of Casey's (1935) experiments were not reported by Shields (1936) and are unknown to **JMB**.

22 Kramer (1935) began measurements of **bedload** transport and other parameters at the start of each experiment, unlike other investigators who waited for some sort of equilibrium condition before making measurements [e.g., Gilbert (1914), Williams

(1970), Wilcock and Southard (1988)]. Reported D_{50m} values were estimated by JMB from Kramer's (1935) Fig. 1, and are again a **best** fit to reported $\tau^*_{c_{r50m}}$ and Re^*_c pairs.

23 Sediment was sand-sized, but other **experimental** details were not reported by Shields (1936) and are unknown to **JMB**. These mixtures are likely non-uniform, based on Day's (1980b) estimates of the USWES (1935) σ_{gm} values.

24 Grain sizes reported are the mean nominal diameters of the laboratory sediment mixture. The **first** $\tau^*_{c_{r50m}}$ and Re^*_c pair correspond with Gilbert's (1914) grade H sediment mixture; no **bedform types** were reported for these runs (Gilbert, 1914). **Bedload** and other measurements were begun when the bed slope equilibrated with the sediment feed rate (Gilbert, 1914). σ_{gm} values were based on the reported range of gram sises in a given **mixture**.

25 **Paintal** (1971) questions the existence of a definitive threshold for mobility, arguing **that** grains exposed to any current will move if one observes them long enough. Nevertheless, two potential $\tau^*_{c_{r50m}}$ values can be estimated from **Paintal's** (1971) analysis. Extrapolating high **bedload** transport rates to a zero value yields $\tau^*_{c_{r50m}} \approx 0.05$ for D_{50m} values, of 2.5 mm and 7.95 mm [**Paintal** (1971), Fig. 8]. Alternatively, a straight line fit **through** a plot of low dimensionless **bedload** transport **rates** versus Shields stresses of **Paintal's** (1971) composite data yields $\tau^*_{c_{r50m}} \approx 0.02$ at a transport rate of 10^{-9} [**Paintal** (1971), Fig. 6].

26 **Mizuyama** (1977) examined the influence of slope and relative roughness on grain mobility, and **proposed** a modified formulation for the Shields stress, accounting for slope and intergranular friction angle. However, a slight mistake in **Mizuyama's** (1977)

force balance resulted in a proposed modified Shields stress of $\tau^*_{c_{r50m}} = \tau_{c_{r50m}} / [(\rho_s - \rho)gD_{50m} \{ \tan\Phi \cos\theta - \sin\theta \rho_s / (\rho_s - \rho) \}]$, rather than the correct expression $\tau^*_{c_{r50m}} = \tau_{c_{r50m}} / [(\rho_s - \rho)gD_{50m}(\tan\Phi \cos\theta - \sin\theta)]$; a buoyancy term was neglected on the left-hand side of Mizuyama's (1977) eqn (3.27) [see Wiberg and Smith (1987) for a similar correct derivation]. Furthermore, the reported intergranular friction angles, Φ , **are** actually angles of repose for the mass sediment mixture [cf. Miller and Byrne (1966)]. Using the correct Shields stress expression (with the erroneous Φ values), JMB calculated $\tau^*_{c_{r50m}}$ values with data from **Mizuyama's** (1977) Tables 3.1 and 3.2. **Mizuyama** (1977) determined $\tau_{c_{r50m}}$ values by extrapolating **bedload** transport rates to a near-zero reference level. **Reported** grain sizes are nominal values of the median (?) grain size of the laboratory sediment mixture; nominal diameters are assumed equivalent to b-axes here (see note 12). σ_{gm} was estimated by JMB from reported sieve ranges. Although the data are not presented here, Mizuyama (1977) also conducted experiments with mixed-grain sediments. It was found that mixed-grain sediments have higher modified Shields stresses than near-uniform grains and that $\tau^*_{c_{r50m}}$ increases systematically with decreasing sorting, contrary to more recent **findings** (Misri et al. 1984; Buffington et al., 1992).

27 Misri and others' (1984) Fig. 6, which is a plot of Einstein's (1950) dimensionless **bedload** transport parameter versus Shields stress stratified by D_i of their N-2 sediment mixture, indicates that dimensionless shear stress is a function of D_i and, more importantly, has no definable critical value over the transport rates that they examined; these **findings agree** with those of Einstein (1950) and **Paintal** (1971). The "critical" Shields stress reported in Table 1 was estimated by JMB from Misri and others' (1984) Fig. 6 based on the lowest transport rate (10^{-4}) of D_i values that bracket D_{50m} .

28 The following criteria were used by Bridge and Dominic (1984) in selecting data sources: use of laboratory sediment mixtures of near-uniform size and density, allowing a mean grain size to be taken as characteristic and avoiding potential armoring effects; and experiments resulting in lower or upper stage plane-beds, minimizing form drag effects. Wall effects were corrected “where necessary” (Bridge and Dominic, 1984). $\tau^*_{c_{r50m}}$ values were determined empirically by plotting dimensionless **bedload** transport rates versus Shields stress, with the critical reference value assumed to be the Shields stress asymptotically approached at low transport rates (Bridge and Dominic, 1984).

29 Collection of **bedload** and other data began only **after** attainment of equilibrium conditions, defined by uniformity of **bedforms** and steady sediment transport rates (Guy et al., 1966). Time to equilibrium varied from hours to **several** days. The 0.19 mm and 0.32 mm runs had water temperatures close to 20° C, but the 0.28 mm runs had water temperatures closer to 15° C; as such, $\nu=1.139 \cdot 10^{-6} \text{ m}^2/\text{s}$ was used in calculating Re^*_c for the 0.28 mm **runs**.

30 **Bedload** and other measurements made after attainment of a constant bed slope and equilibrium of sediment input and output (Williams, 1970).

31 $\tau^*_{c_{r50m}}$ determined from the composite experiments of Fernandez Luque and van Beek (1976). Five different laboratory sediment mixtures were used with mean (by weight) grain sizes of 0.9-3.3 mm and densities of 1340-4580 kg/m^3 . See also note 42.

32 $\tau^*_{c_{r50m}}$ values correspond with extrapolated zero or **near-zero bedload** transport rates and were calculated by JMB using Bathurst and others' (1987) eqn (15.1) and values in Table 15.3. Equation (15.1) is a modified Shields stress, accounting for slope and

intergranular friction angle. However, reported friction angles are actually angles of repose of the mass sediment **mixture**, not intergranular friction angles [cf. Miller and Byrne (1966)]. **Re*_c values** estimated from **Bathurst** and others' (1987) Fig. 15.3.

33 Reported grain sizes and relative roughnesses are from **Bathurst** et al. (1983). Details of **Bathurst** and others' (1979) flume experiments **are** unknown to JMB. **$\tau^*_{c_{r50m}}$ values** were determined by **Bathurst** et al. (1979) as per note 32 and were estimated by **JMB** from **Bathurst** and others' (1987) Fig. 15.3. It is uncertain, however, if **Bathurst** and others' (1979) values were corrected for sidewall effects.

34 Using the Ackers and White (1973) **bedload** transport equation, Day (1980b) extrapolated **fractional bedload** transport rates to a low reference **value** assumed representative of incipient motion and determined corresponding initial motion parameters for **D_i** of **bedload** experiments conducted by **USWES** (1935) and Day (1980a). **$\tau^*_{c_{r50m}}$ values** were determined by JMB from Day's (1980b) Fig. 41.4 for dimensionless particle sizes corresponding with **D_{50m}** values of the flume experiments [Table 41.1, Day (1980b)]; the Ackers and White (1973) initial motion parameter in Fig. 41.4 is simply the **square** root of the Shields equation. Few details of the experimental methods and conditions were presented by Day (1980b). Using Day's (1980b) reported values of $(D_{84m}/D_{16m})^{0.5}$ (Table 41.1), **σ_{gm}** was calculated by JMB as **$\sigma_{gm}=[\log_2(D_{84m}/D_{16m})-\log_2(1)]/2$** .

35 Using Parker and Klingeman's (1982) technique (note I), **$\tau^*_{c_{ri}}$ values** were determined and expressed as a function of the ratio **D_i/D_{50m}** (Wilcock and **Southard**, 1988). **$\tau^*_{c_{r50m}}$ values** were calculated by JMB from these functions [Table 6, Wilcock and

Southard (1988)], taking $D_i/D_{50m}=1$. **Wilcock's** (1987) data were corrected for form drag and sidewall effects, but it is uncertain if Wilcock and Southard (1988) applied similar corrections to the other data sources that they used. Misri et al. (1984) applied sidewall and (?) form drag corrections, but analytical procedures of Day (**1980a**) and Dhamotharan et al. (1980) are unknown to JMB. For the data of Misri et al. (**1984**), Dhamotharan et al. (**1980**), and Wilcock and **Southard (1988)**, σ_{gm} was calculated from D_{15m} and D_{85m} values reported by Wilcock and Southard (1988, Table 1). σ_{gm} values for Day's (**1980a**) experiments are the same as those described in note 34.

36 **Bedload** and **other** measurements were made after attainment of equilibrium conditions, defined by steady sediment transport and stable **bedforms** (**Wilcock** and Southard, 1988). To better establish initial motion conditions several runs for each sediment mixture involved lower stage plane-bed morphologies. **Bedload** transport rates for these runs **were** close to the assumed reference value (Wilcock and Southard, 1988). Water temperatures were typically about 25' C and as such I used $v=0.893 \cdot 10^{-6} \text{ m}^2/\text{s}$ in calculating Re^*_c values.

37 Kramer (1935) recognized **three** types of visual grain movement: weak, characterized by infrequent movement of a small number of the finest grain sizes of the sediment mixture; medium, characterized by movement of a significant number of the mean grain sizes (and smaller), but with insignificant **bedload** transport and maintenance of a **plane-bed** morphology; and general, characterized by significant movement of all grain sizes, an appreciable quantity of **bedload** transport, and dune-ripple development. Because mobility of the median grain size is the issue here, the data reported in Table 1.1 are

values corresponding with “medium” bed surface mobility of each sediment mixture.

D_{50m} values estimated by JMB from Kramer’s (1935) Fig. 1.

38 $\tau^*_{c_{v50m}}$ was calculated from the Meyer-Peter and Müller (MPM) **bedload** equation employing the observed τ_c and assuming a **zero** transport rate at incipient motion (Meyer-Peter and Müller, 1948). The MPM equation expresses **bedload** transport of the composite bed material in terms of the “effective diameter” of the laboratory sediment mixture, defined as $\Sigma D_i f_i$, where D_i is the average grain size within a given **size** class of the weight distribution and f_i is that class’ fraction of the distribution. The effective diameter was typically equivalent to D_{50-60m} (Meyer-Peter and Müller, 1948).

39 Threshold of mobility defined by visual observation of either the initiation or cessation of motion (White, 1940). The first two $\tau^*_{c_{v50m}}$ and Re^* pairs were calculated by JMB from White’s (1940) Table 1 (experiments la-b and 2a) assuming $\rho_s=2650 \text{ kg/m}^3$ and $\rho=900 \text{ kg/m}^3$; the density of the fluid was estimated by comparing the reported **depth-slope** products [Table 1, “from d,” White (1940)] with those calculated by JMB for a fluid medium of water. The third $\tau^*_{c_{v50m}}$ and Re^* pair was calculated by JMB from data on pg. 328 assuming $v=10^{-6} \text{ m}^2/\text{s}$. All other values from White’s (1940) Table 2.

40 Boundary shear stress was measured from photographed velocity profiles defined by hydrogen bubbles traces (Grass, 1970). Two measures of shear stress are reported by Grass: 1) an average value **determined** from 25 of the instantaneous velocity **profiles selected at random throughout the measuring period; 2) an instantaneous value** interpolated from the instantaneous velocity profiles just before and **after** incipient motion (as identified from photographs of the bed surface). $\tau^*_{c_{v50m}}$ values determined from the later measures are reported in Table 1 in **parentheses**. $\tau^*_{c_{v50m}}$ values calculated

from the former measures are more comparable to a depth-slope **value** in that they are a time-averaged measure; however, it is unclear if the randomly selected velocity profiles of a given run are sampled **from** similar conditions of flume-average flow depth and slope. Direct shear stress measures of this sort implicitly account for sidewall effects.

41 $\tau^*_{c_{v50m}}$ values calculated by JMB using the Shields equation and data in **Everts'** (1973) Table 1. Re^*_c was calculated with $v=0.893 \cdot 10^{-6} \text{ m}^2/\text{s}$, as Everts (1973) reports a water temperature of about 25° C.

42 Fernandez Luque and van Beek (1976) examined the effects of bed surface slope on $\tau^*_{c_{v50m}}$ values and as expected found a systematic increase in $\tau^*_{c_{v50m}}$ with slope; the Shields equation as originally written neglects the downslope gravitational component of the driving force. $\tau^*_{c_{v50m}}$ values reported in Table 1.1 are for 0° bed slopes and were estimated by JMB from Fernandez Luque and van **Beek's** (1976) Fig. 2. $\tau_{c_{v50m}}$ values were calculated from a **standard** Moody diagram, using measured velocities and an hydraulic radius corresponding with the center 0.05 m of the flume bed (Fernandez Luque and van Beek, 1976); **this** technique implicitly accounts for sidewall effects,

43 σ_{gm} was estimated by JMB from D_{10m} and D_{90m} , knowing that $1.6 \leq D_{90m}/D_{10m} \leq 2.1$ for the sediment mixtures employed in Yalin and **Karahan's** (1979) experiments. The estimation is $\sigma_{gm} \approx [\log_2(D_{90m}/D_{10m}) - \log_2(1)]/2$.

44 The same technique was used as in note I, however, $\tau^*_{c_{Ti}}$ values were expressed as a function of D_j/D_{50ss} . σ_{gss} was calculated by JMB from data presented in Parker and Klingeman's (1982) Table 1.

45 $\tau^*_{c_{q50ss}}$ values were determined by **JMB** from reported $\tau^*_{c_{qi}}$ functions [**Komar (1987a)**, Table 1], with $D_i/D_{50ss}=1$. Note that $\tau^*_{c_{q50}}$ values were fit by Komar to the Shields curve developed by Miller et al. (1977), and as such are **fixed** by default at values of 0.045 for **high Re^*_c** values (see note 6). σ_{gss} was calculated by **JMB** from D_{10ss} and D_{90ss} values presented in Milhous' (1973) Table 3.