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A PROCESS-BASED STREAM CLASSIFICATION SYSTEM FOR SMALL STREAMS IN WASHINGTON

Prepared By

Jeffrey B. Bradley and Peter J. Whiting

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WEST Consultants, Inc.
810 - 3rd Ave., Suite 408
Seattle, WA 98104

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INTRODUCTION

A fundamental prerequisite for the application of landuse regulations to the natural domain is the identification of those parts of a landscape that are environmentally sensitive and warrant various degrees of protection. This is particularly true in the evaluation of forest practices, which depending on the geometry of a hillslope, the character of the stream channel, and the history of the drainage basin, have notably different consequences upon fish, wildlife and water quality. This report, commissioned by the Sediment and Mass Wasting Committee (SHAMW) of the Cooperative Monitoring, Evaluation and Research Committee (CMER), outlines a geomorphically process-based stream classification system for small forest streams which provides the framework for building rational landuse regulations.

The stream typing system presently used in the State of Washington is based on an assortment of factors including channel size, water use and fisheries. Type 4 and 5 waters are defined as those not containing anadromous fisheries (WAC 222-16-030) whereas Types 1-3 do contain anadromous or resident fisheries. Channel size generally decreases from Type 1 through Type 5. The present system does not consider stream process or geomorphology except as size is associated with stream type. Best management practices (BMPs) mandated for environmental protection vary significantly between Types 1-3, and Type 4 and 5 streams. BMPs for forests in Washington govern activities conducted on or directly pertaining to forested lands and related to growing, harvesting, or processing of timber. Specific issues of concern include roads, timber harvest, silvicultural practices, and riparian management zones. Of particular significance is that riparian zone practices vary dramatically between Type 3, 4, and 5 streams. Consequently, downstream effects on beneficial uses (fisheries, water quality, etc.) are not well understood in terms of physical process. A 1989 review (MacDonald and Ritland) for the SHAMW revealed a definite need for improvement of descriptive techniques for small streams. It may be that an improved physically based channel identifier will result in more accurate appraisals of channel sensitivity, and at the same time yield more general support from a regulatory viewpoint. At present the local forester and even the scientific expert has trouble with such delineations because they are often poorly correlated to environmental sensitivity. The reason for this is that the present system is based upon stream size, fisheries, and water use rather than upon an understanding of physical processes that determine environmental sensitivity.

To date, only limited research information on stream processes, forest practices, and related effects on downstream beneficial uses is available for Type 4 and 5 waters within the state of Washington. Debris flows and debris avalanches are thought to be the dominant physical processes in such streams in the western Cascades, the northwest coast and, on a less frequent basis, in the eastern Cascades, Blue Mountains and southwestern Washington. Bank erosion, channel bed erosion and streamside rotational slides are important sediment sources throughout Washington. Sediment storage in headwater streams is strongly tied to channel obstructions, and the amount of woody debris including large organic debris (LOD). On the west side of the Cascades channel recovery following a debris flow, avalanche, or undifferentiated debris torrent, is generally thought to be rapid with significant reduction in sediment supply within a decade following a disturbance. The time frame for recovery is longer east of the Cascade divide but the occurrences are less frequent. The direct effects of debris flows are usually limited to headwater reaches or where steep tributary channels enter mainstem valleys. On occasions debris flows or dam break floods may "run out" along lengthy portions of the channel generating disturbances and sedimentation problems well down the channel network. Increased fluxes of fine sediment are often noted well downstream of debris flows.

The first section of this report is a timely overview of previously proposed stream classifications. The next section develops a process-based, geomorphic classification system for small streams that takes into account the drainage's propensity for mass wasting and the channel's capacity for transporting material. Downstream impacts as related to stream class are then presented. In conclusion, we present an appraisal of the classification scheme based upon our own field study and the comments of solicited experts.

BACKGROUND

Classification of Channel Patterns

All streams and rivers may be separated into two major groups depending on their freedom to adjust their shape and gradient. Bedrock controlled channels are those so confined between outcrops of rock that the material forming their bed and banks determines the morphology of the channel. Alluvial channels, on the other hand, are free to adjust dimensions, shape, pattern and gradient in response to change, and they flow through a channel with bed and banks composed of the material transported by the stream. Type 4 and 5 streams include both bedrock and alluvial streams. The following discussion is a review of various stream classifications developed primarily for alluvial streams.

Despite the prolonged interest of geomorphologists and engineers in stream classification, no totally definitive system has been accepted. Alluvial channels are dynamic and subject to both rapid and slow changes which can be quite different and highly variable from site to site and year to year. Alluvial channel patterns are the cumulative result of climatic, geologic, topographic, hydrologic factors, and water resources development. Classification systems are usually of two general types; one based on planform evaluation of alluvial channels and the other based on the independent variables which determine channel morphology. The most basic channel pattern classification defines three types of stream planform; straight, meandering, and braided. A straight channel has straight and parallel banks. A meandering channel is a single thread channel consisting of bends with short straight crossings between bendways. A braided stream is a multi-thread channel with islands, bars, and secondary channels.

Descriptive classifications of river pattern planform have been extensively summarized by Brice (1974), Dury (1969), and Kellerhals, Church and Bray (1976). In Brice's classification the channel properties that are of importance are the degrees of sinuosity, braiding and anabranched streams. A channel with sinuosity (sinuosity = ratio of thalweg length to valley length) less than 1.05 is straight, one between 1.05 and 1.25 is sinuous, and one with sinuosity greater than 1.25 is meandering. The degree of braiding is the percentage of channel length that is divided by islands or bars. He similarly defined the degree of anabranching as the percentage of reach length occupied by large semi-permanent bars or islands. A summary of this method is shown in Figure 1. Dury (1969) developed a general inventory of channel planform directly from observation which recognized eight channel types; meandering, braided, straight, straight-simulating, deltaic distributory, anabranching, reticulate, and irregular. Kellerhals, Church and Bray (1976), as shown in Figure 2, proposed a classification defining channel features under three major headings; channel pattern, islands, and channel bars and major bed forms. In more recent studies, these authors have proposed a simpler breakdown of planform into meandering, braided, split and anastomosing channels. All of the previous authors extended the basic planform classification for several reasons, the main one being that the terms are not mutually exclusive. Single thread channels can meander in distinctly different modes, while multiple thread streams present even greater descriptive difficulty. Planform can also be a function of river stage, which further complicates the issue.

Another common approach to stream pattern classification considers two independent variables, streamflow and type of sediment load, which partially control the morphology of alluvial channels. Variations on this theme have been developed by Schumm (1963), Schumm and Parker (1973), Allen (1965), and Mollard (1973). As summarized in Table 1, Schumm originally chose a classification approach which considered the channel's stability and mode of sediment transport. Schumm and Meyer (1979) extended this general methodology to qualitatively classify five types of alluvial channel planforms (Figure 3). Allen (1965) modified Schumm's original work in terms of the lateral stability of channels and presented a continuum of channel forms. Mollard (1973) further developed the continuum approach permitting the qualitative assessments of discharge, sediment supply, ratio of bed material load to total sediment load, channel gradient, channel sinuosity and channel stability with relation to channel pattern.

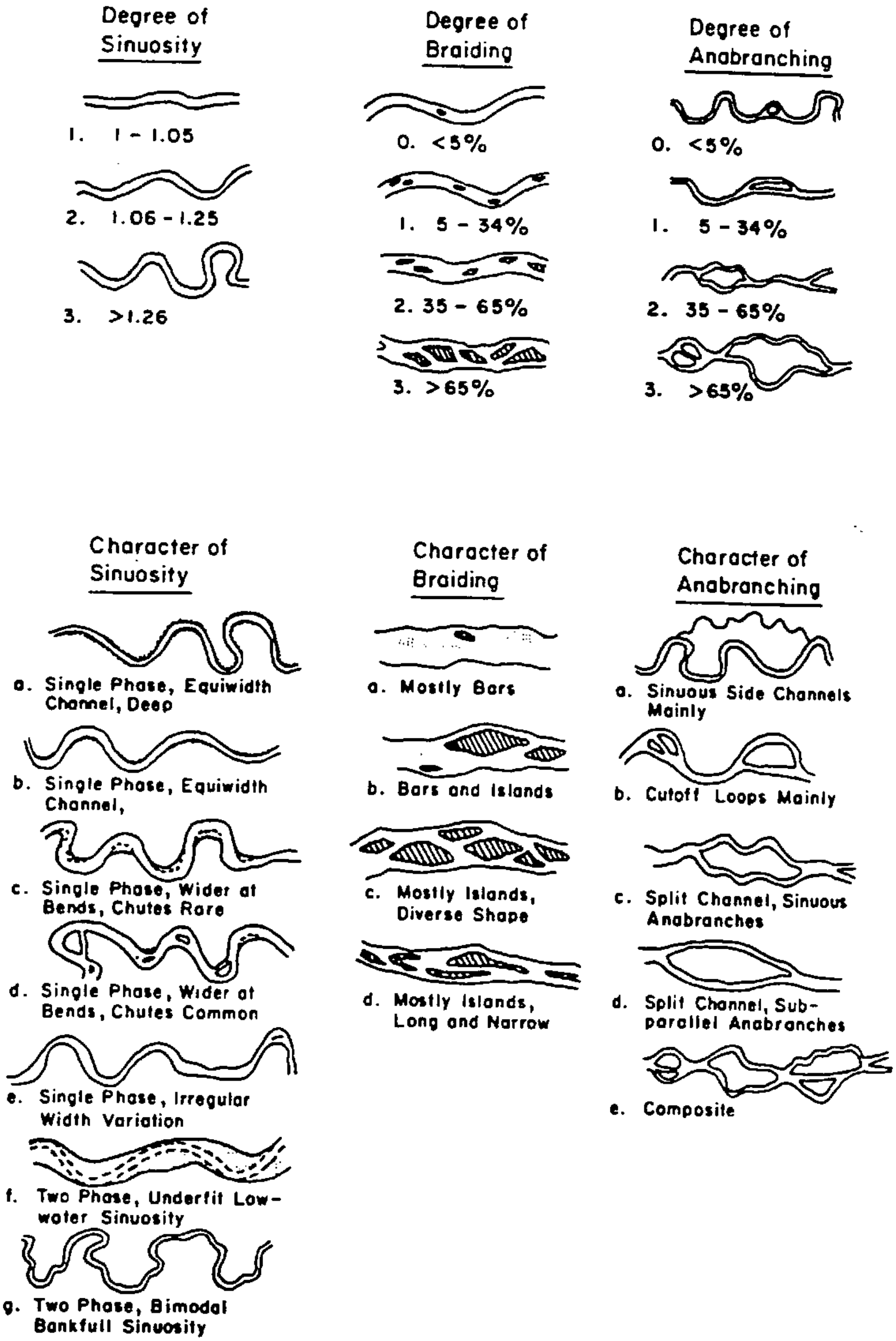
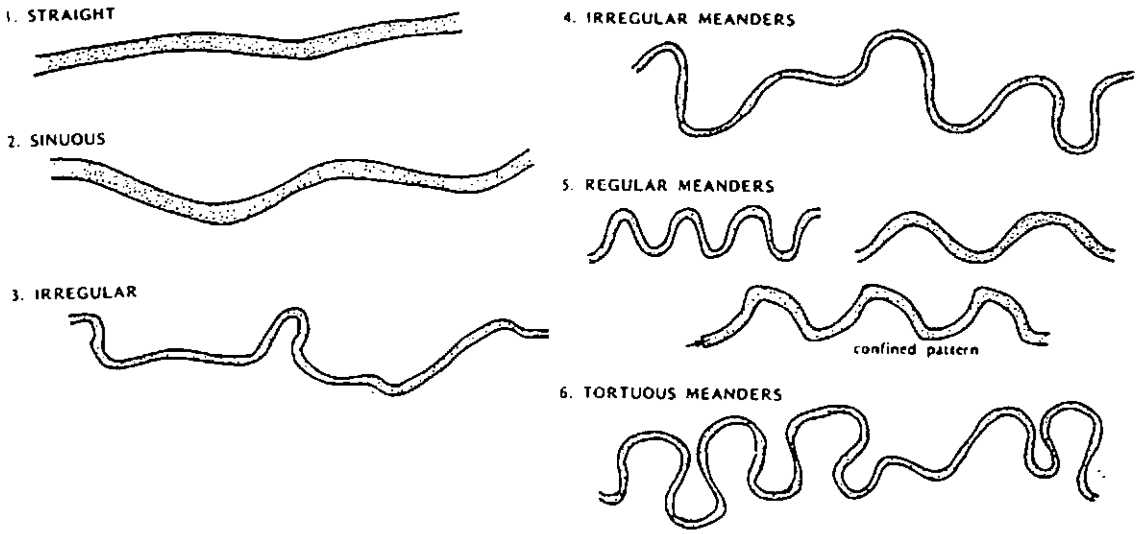
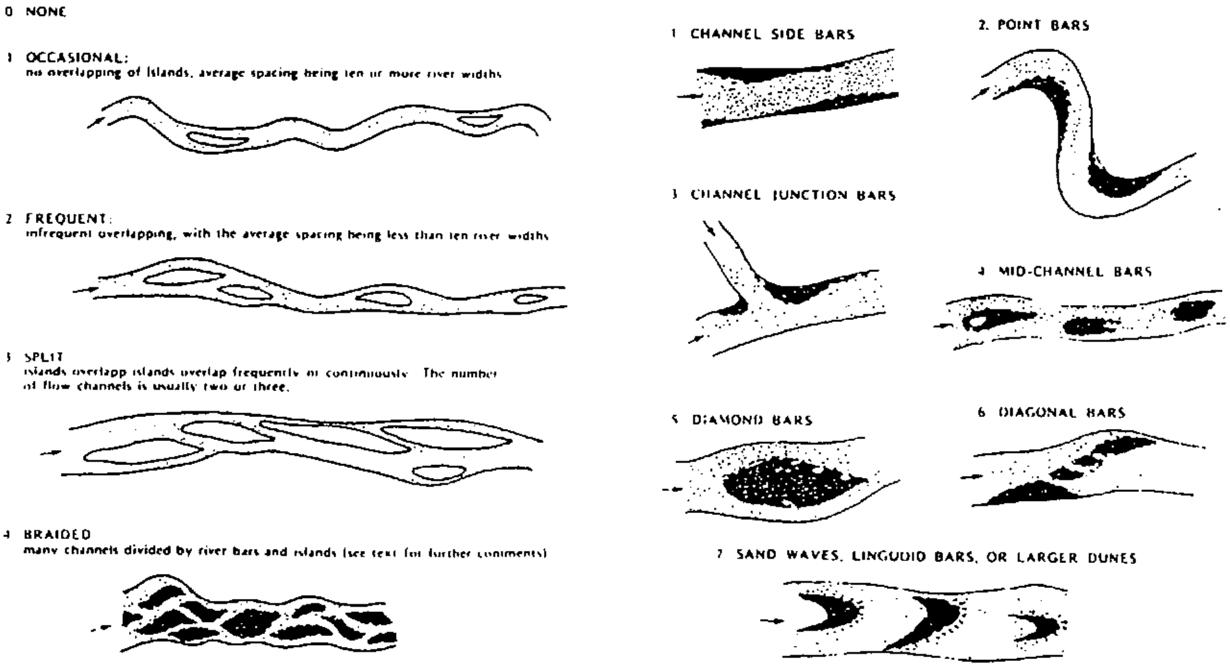


Figure 1. Brice's Stream Classification



Codification of River Channel Patterns



Codification of Islands

Codification of River Channel Bars

Figure 2. Kellerhals, Church and Bray Classification

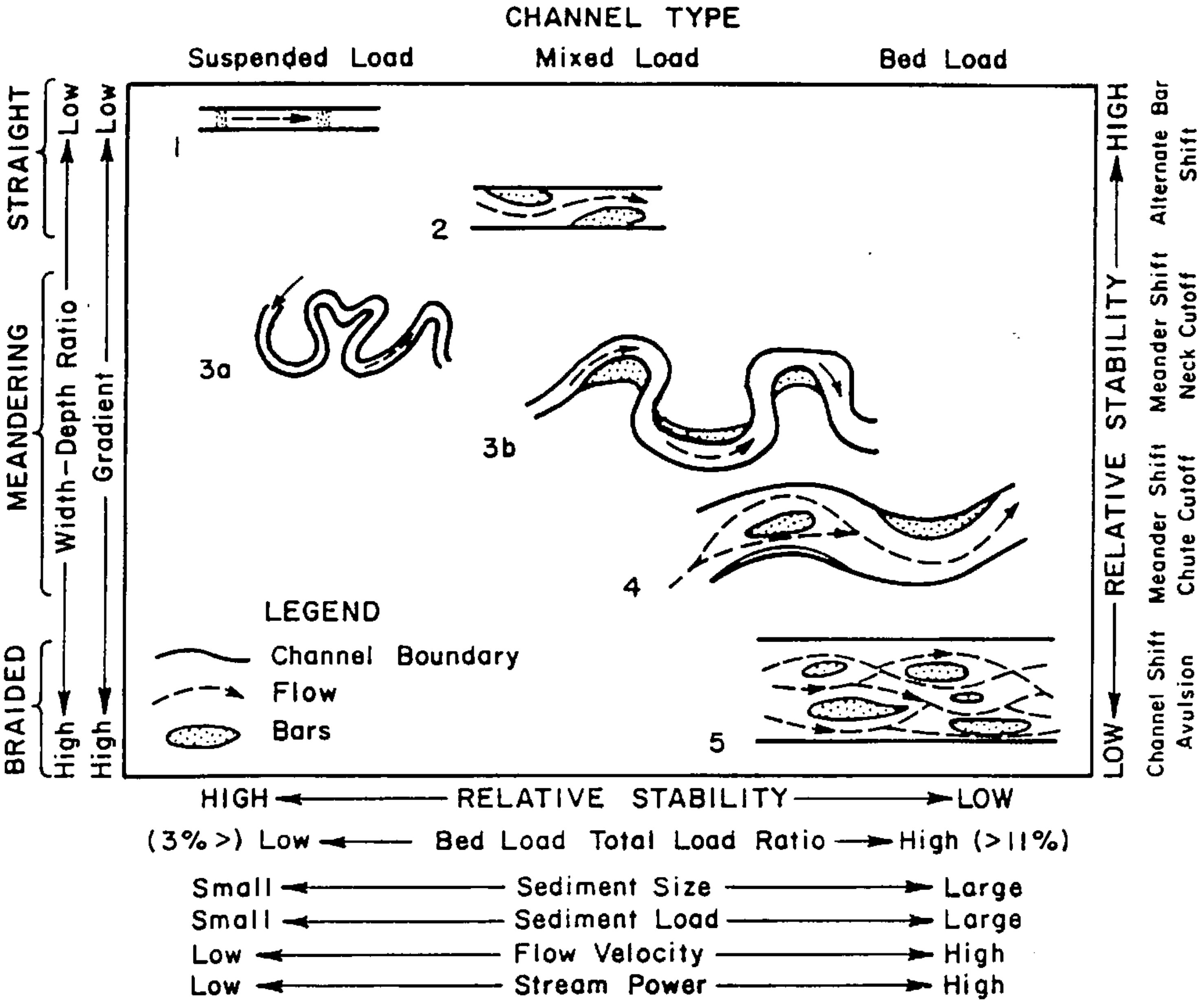


Figure 3. Schumm and Meyer Stream Classification

Mode of sediment transport and type of channel	Channel sediment (*M*) (percent)	Bedload (percentage of total load)	Channel stability		
			Stable (graded stream)	Depositing (excess load)	Eroding (deficiency of load)
Suspended load	>20	<3	Stable suspended-load channel. Width/depth ratio <10; sinuosity usually >2.0; gradient, relatively gentle	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; initial streambed deposition minor	Eroding suspended-load channel. Streambed erosion predominant; initial channel widening minor
Mixed load	5–20	3–11	Stable mixed-load channel. Width/depth ratio >10, <40; sinuosity usually <2.0, >1.3; gradient, moderate	Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition	Eroding mixed-load channel. Initial streambed erosion followed by channel widening
Bed load	<5	>11	Stable bed-load channel. Width/depth ratio >40; sinuosity usually <1.3; gradient, relatively steep	Depositing bed-load channel. Streambed deposition and island formation	Eroding bed-load channel. Little streambed erosion; channel widening predominant

Table 1. Schumm's Stream Pattern Classification

A third type of stream classification is that of Rosgen (1985). The purpose of this classification scheme, and others like it, is to categorize stream channels on the basis of measurable morphological features. Rosgen used channel gradient, sinuosity, width/depth ratio, dominant particle size of channel material, channel entrenchment/valley confinement, and landform feature. His stream classification criteria are presented in Table 2. Various spinoffs of Rosgen's method have been applied to specific geographic regions, primarily within National Forests such as the Tongass of southeast Alaska (Bradley and Reiser, 1991).

Channel Pattern Prediction

Alluvial channel patterns are generally classified in their most basic form as straight, meandering or braided and pattern type is thought to depend on discharge (streamflow), slope, and sediment load. Quantitative pattern thresholds are potentially valuable to geomorphologists and engineers but existing knowledge is weakened by incomplete and inconsistent pattern classification, difference in operational definitions, and lack of qualitative or quantitative theory. A range of quantitative threshold models have been developed to describe pattern adjustments in response to changing control variables such as discharge, bed material size, bank material properties, and valley slope. Another approach in assessing channel patterns is to define a common morphological variable such as sinuosity to describe a continuum of pattern variation in response to differing stream power. This method can provide a qualitative understanding of the interplay of stream power and erodibility.

A number of threshold models have been developed, one of the first being that of Leopold and Wolman (1957). Leopold and Wolman directly discriminated between braided and single thread channels using slope and bankfull discharge (Figure 4). In this discussion it should be noted that multiplication of slope and discharge produces stream power (sometimes it is the velocity-slope product). This technique does not include an accounting of bed and bank material. Lane (1957), using a similar technique, presented a breakdown between meandering, intermediate, and braided patterns using the parameters, slope and mean annual discharge (Figure 5). Differences between the two approaches are due to river prototype data and the

CRITERIA FOR STREAM TYPES

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT VALLEY CONFINEMENT	LANDFORM FEATURE SOILS & STABILITY
A1	4-10	1.0-1.1	10 or less	Bedrock	Very deep/ very well confined	Deeply incised bedrock drainageway w/ steep side slopes or vertical rock walls.
A1-a	10 +	(Criteria same as A1)				
A2	4-10	1.1-1.2	10 or less	Large & small boulders w/ mixed cobble.	Same	Steep side slopes w/predominantly stable materials.
A2-a	10 +	(Criteria same as A2)				
A3	4-10	1.1-1.3	10 or less	Small boulders W/ cobble, coarse gravel.	Same	Steep, depositional features w/ predominantly coarse textured soils. Debris avalanche is the predominant erosional process. Stream adjacent slopes are rejuvenated with extensive exposed mineral soil.
A3-a	10 +	(Criteria same as A3)				
A4	4-10	1.2-1.4	10 or less	Predominantly gravel, sand some silts.	Same	Steep slide slopes w/mixture or either depositional landforms with fine textured soils such as glacioflvial or glaciolacustrine deposits or highly erodible residual soils such as grussic granite, etc. Slump-earthflow and debris avalanche are dominant erosional processes. Stream adjacent slopes are rejuvenated.
A4-a	10 +	(Criteria same as A4)				
A5	4-10	1.2-1.4	10 or less	Silt and/or clay bed and bank materials.	Same	Moderate to steep side slopes. Fine textures cohesive soils, slump-earthflow erosional processes dominate.
A5-a	10+	(Criteria same as A5)				
B1-1	1.5-4.0	1.3-1.9	10 or greater ($\bar{X}$:15)	Bedrock bed, banks, cobble, gravel, some sand.	Shallow entrenchment moderate confinement.	Bedrock controlled channel with coarse textured depositional bank materials.
B1	2.5-4.0	1.2-1.3	5-5 ($\bar{X}$:10)	Predominantly small boulders, very large cobble	Moderately entrenched/ well confined.	Moderately stable, coarse textured resistant soil materials. Some coarse river terraces.

Table 2. Rosgen's Stream Classification

CRITERIA FOR STREAM TYPES

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT VALLEY CONFINEMENT	LANDFORM FEATURE SOILS & STABILITY
B2	1.5-2.5 ($\bar{X}$:2.0)	1.2-1.5	8-20 ($\bar{X}$:14)	Large cobble mixed w/small boulders & coarse gravel	Moderately entrenched Moderately confined.	Coarse textured, alluvial terraces with stable, moderately steep, side slopes
B3	1.5-4.0 ($\bar{X}$:2.5)	1.3-1.7	8-20 ($\bar{X}$:12)	Cobble bed w/ mixture of gravel & sand - some small boulders.	Mod. entrenched/ well confined.	Glacial outwash terraces and/or rejuvenated slopes. Unstable, moderate to steep slopes. Unconsolidated, coarse textured unstable banks. Depositional landforms.
B-4	1.5-4.0 ($\bar{X}$:2.0)	1.5-1.7	8-20 ($\bar{X}$:10)	Very coarse gravel w/cobble mixed sand and finer material.	Deeply entrenched well confined.	Relatively fine river terraces. Unconsolidated coarse to fine depositional material.Steep side slopes. Highly unstable banks.
B5	1.5-4.0 ($\bar{X}$:2.5)	1.5-2.0	8-25 ($\bar{X}$:15)	Silt/clay.	Same	Cohesive fine textured soils. Slump earthflow erosional processes.
C1-1	1.5 or less ($\bar{X}$:1.0)	1.5-2.5	10 or greater ($\bar{X}$:30)	Bedrock bed, gravel, sand, or finer banks.	Shallow entrenchment poorly confined.	Bedrock controlled channel with depositional fine grained bank material.
C1	1.2-1.5 ($\bar{X}$:1.3)	1.5-2.0	10 or greater ($\bar{X}$:18)	Cobble bed with mixture of small boulders & coarse gravel.	Mod. entrenched/ Mod. confined.	Predominantly coarse textured, stable high alluvial terraces.
C2	0.3-1.0 ($\bar{X}$:0.6)	1.3-1.5	15-30 ($\bar{X}$:20)	Large cobble bed w/ mixture of small boulders & gravel.	Mod. entrenched well confined.	Overfit channel, deeply incised in coarse alluvial terraces and/or depositional features.
C3	0.5-1.0 ($\bar{X}$:.8)	1.8-2.4	10 or greater ($\bar{X}$:22)	Gravel bed w/ mixture of small cobble & sand.	Mod. entrenched slight confined.	Predominantly moderate to fine textured multiple low river terraces. Unstable banks, unconsolidated, noncohesive soils.
C4	0.1-0.5 ($\bar{X}$:.3)	2.5 +	5 or greater ($\bar{X}$:25)	Sand bed w/ mixtures of gravel & silt (no bed armor)	Mod. entrenched slight confined.	Predominately fine textured, alluvium with low flood terraces.

Table 2. Continued.

CRITERIA FOR STREAM TYPES

STREAM TYPE	GRADIENT	SINUOSITY	W/D RATIO	DOMINANT PARTICLE SIZE OF CHANNEL MATERIALS	CHANNEL ENTRENCHMENT VALLEY CONFINEMENT	LANDFORM FEATURE SOILS & STABILITY
C5	0.1 or less ($\bar{X}$:.05)	2.5 +	5 or greater ($\bar{X}$:10)	Silt/clay w/ mixtures of medium to fine sands (no bed armor).	Mod. entrenched/ slight confined.	Low, fine textured alluvial terraces. Delta deposits, lacustrine, loess or other fine textured soils. Predominantly cohesive soils.
C6	0.1 or less ($\bar{X}$:.05)	2.5 +	3 or greater ($\bar{X}$:5)	Sand bed w/ mixture of silt & some gravel.	Deep entrenched slight confined.	Same as C4 except has more resistant banks.
D1	1.5 or greater (X:2.5)	N/A Braided	N/A	Cobble Bed w/ mixture of coarse gravel & sand & small boulders.	Slight entrenched/ no confinement.	Glacial outwash, coarse depositional material, highly erodible. Excess sediment supply of coarse size material
D2	1.5 or less ($\bar{X}$:1.0)	N/A Braided	N/A	Sand bed w/ mixture of small to medium gravel & silts.	Slight entrenched/ no confinement.	Fine textured depositional soils, very erodible - excess of fine textured sediment.

E. Estuarian Streams (Deltas)

E1. High Constructive - Lobate shaped deltas with a wide, well defined delta plain and numerous distributary channels.

E2. High Constructive - Elongate deltas with a narrow delta plain with lateral distributary channels.

E3. High Destructive - Tide dominated deltas.

E4. High Destructive - Wave dominated deltas.

G. Glacial Streams

G1. Streams incised in glacial ice with mixture of tills involving coarse textured materials including small boulders, cobble, gravels, sands, and some silt.

G2. Streams incised in glacial ice with materials of silts, clays and some sands. Typical of glacial lacustrine deposits.

Table 2. Continued.

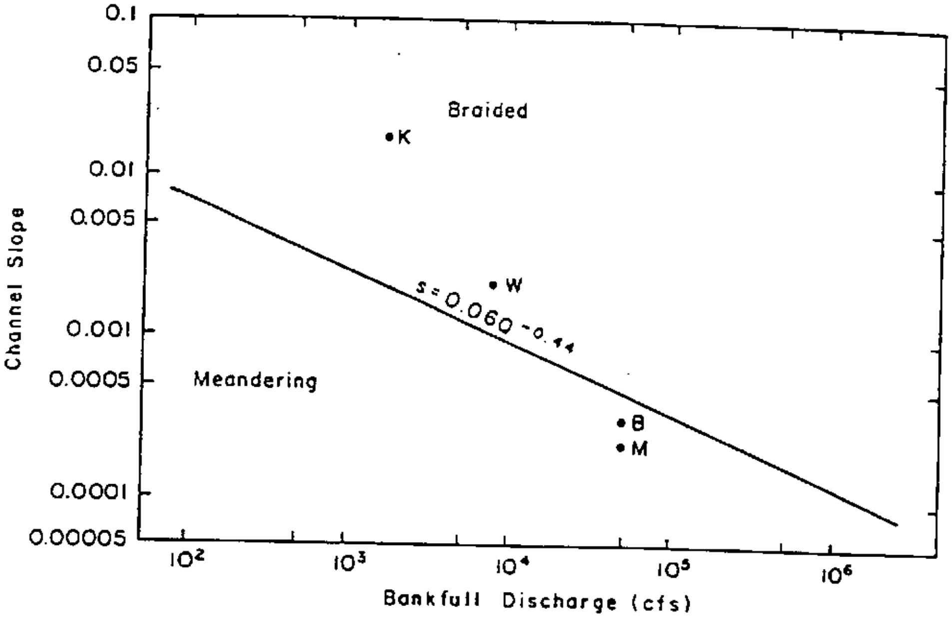


Figure 4. Leopold and Wolman's Stream Pattern Predictor.

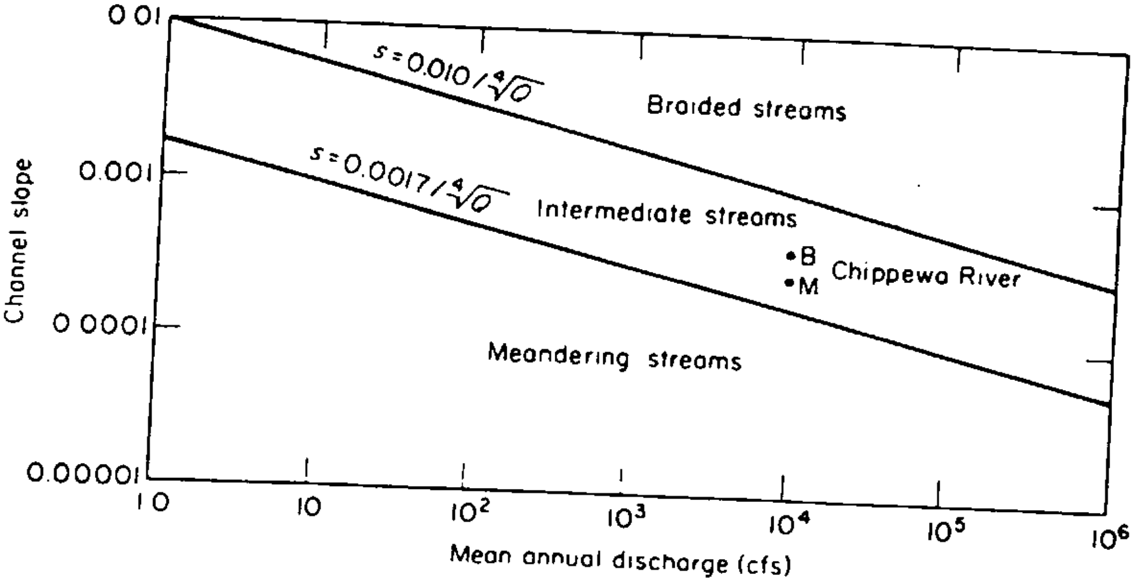


Figure 5. Lane's Threshold Pattern Predictor.

definitions of river patterns. Lane's method was developed for sand bed streams while Leopold and Wolman's was developed for predominantly gravel bed streams. Henderson (1963) discriminated between straight and meandering channels using slope, discharge and bed material size (Figure 6). Church and Kellerhals (Church, 1984) used the same approach to define the threshold between wandering and braided channel patterns in Canadian streams. Osterkamp (1978) performed an analysis similar to that of Lane for sand bed streams in Kansas. He also recognized the importance of sediment size and sinuosity and proposed variables to account for these parameters. Bray (1982) also based his analysis of channel pattern for gravel bed streams on discharge and slope. In 1984, Ferguson re-evaluated the methods of Leopold and Wolman, Henderson, Bray, Lane and Osterkamp. Using a data set composed primarily of braided and near-braided river data, Ferguson developed a best fit discriminant function which included a sediment grain size parameter (Figure 7).

A more theoretically based threshold approach was presented by Anderson, Parker and Wood (1975) which defined the meandering-braiding threshold to be a function of the slope/Froude number ratio and the width/depth ratio (Figure 8). This criterion can be converted to a slope/discharge discriminant by relating Froude number, $V/(gD)^{1/2}$, where V is mean velocity, g the acceleration of gravity, and D the hydraulic depth, and width/depth ratio to discharge. All of the above threshold approaches can be divided into discriminants using slope and discharge; or slope, discharge and bed material size. Fredsoe (1978) developed a hydrodynamic stability analysis to predict whether a channel would braid, meander, or remain straight. He constructed threshold curves which incorporated the Shields coefficient and therefore allowed for consideration of bed material size, bed shear stress and channel slope. He also delineated between flow over a dune covered bed and a plane bed. These thresholds vary depending on the prototype and flume data used in their development, and on the various authors' definitions of channel pattern.

Smith (1987) compared nine methods, seven empirical and two theoretical, for predicting whether streams should braid or meander based upon a data set of 101 stream channels. His results indicated the importance of considering bed material size in any analysis, as well as the

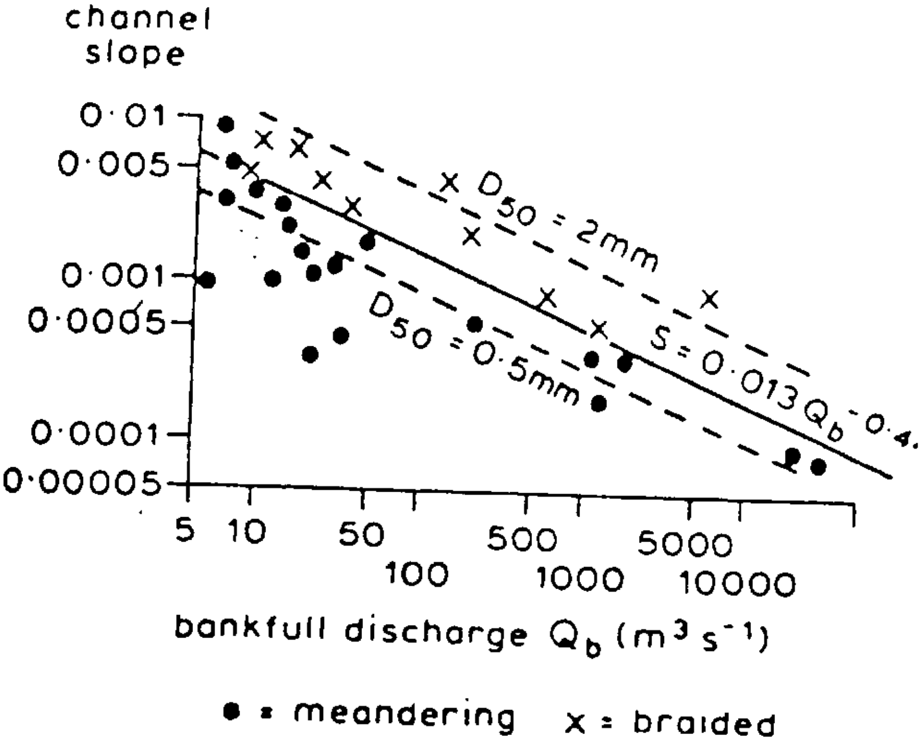


Figure 6. Henderson Stream Pattern Predictor.

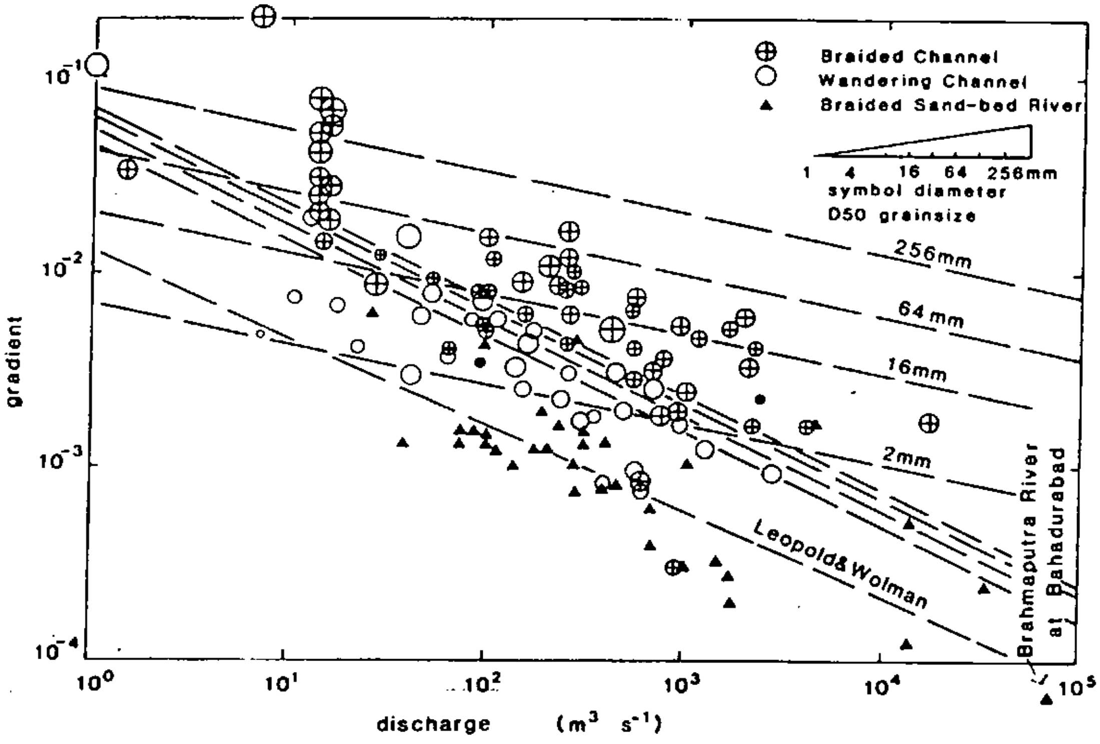


Figure 7. Ferguson Stream Threshold.

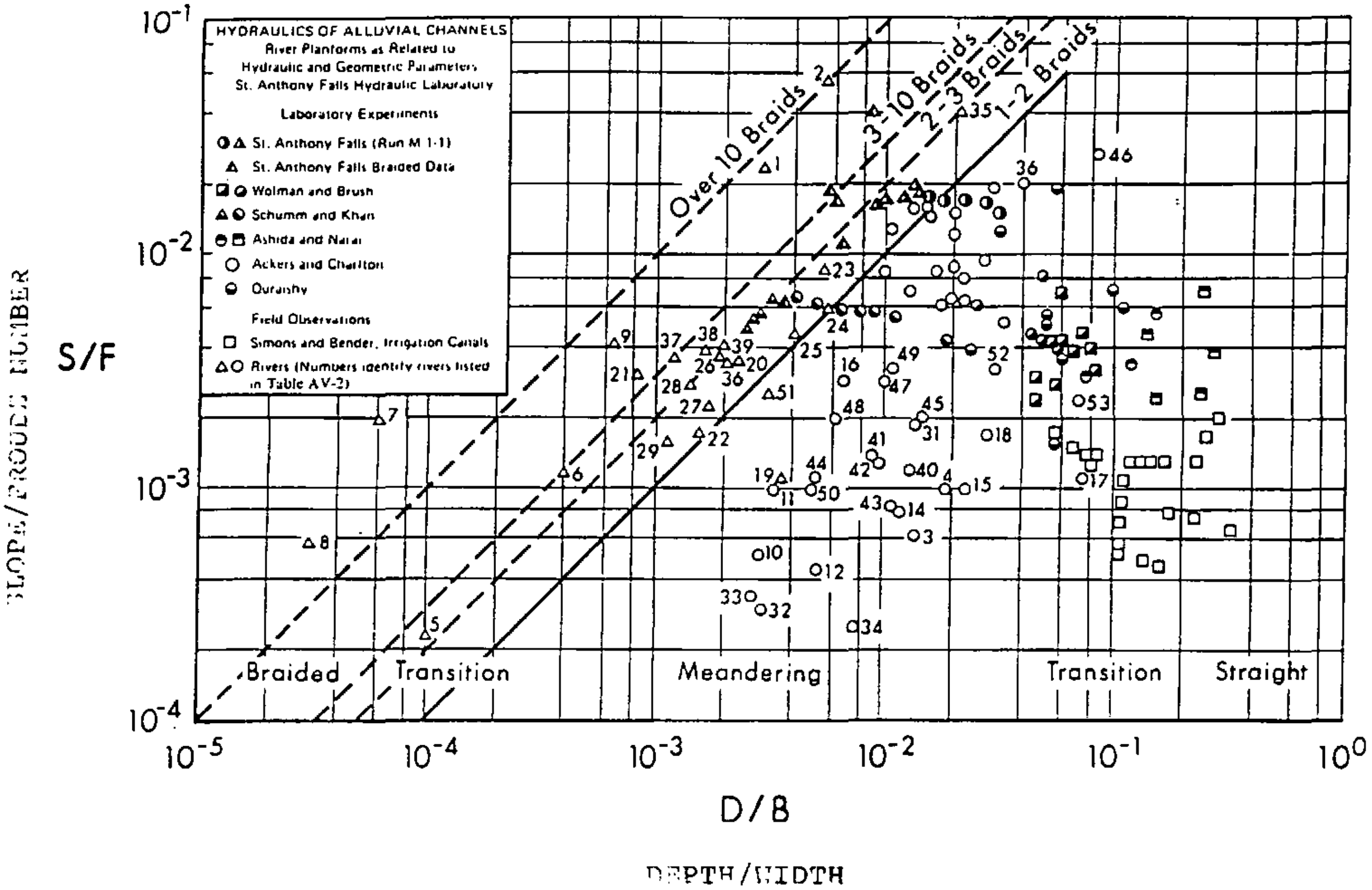


Figure 8. Anderson, Parker and Wood Stream Threshold.

need to choose a method which was developed for conditions similar to those being studied. He recommended the use of Lane's (1957) method for use in sand bed streams, Ferguson's (1984) method in gravel bed streams, and Fredsoe's (1978) method for use with all 101 streams without discriminating by grain size.

The continuum approach, as presented by Schumm and Khan (1973), defines a morphologic term, sinuosity, as a continuous variable to describe straight, meandering and braided channels as a function of stream power (Figure 9). With increasing stream power, a channel will progress from straight to meandering with high sinuosity to braided with small sinuosity. The difference between the continuum approach of Schumm and Khan, as compared to the threshold methods, is summarized in Figure 10. A similar approach developed by Richards (1982) used sinuosity and exponential of stream power. Richards uses a different definition of sinuosity which is based upon a measure of bed area per length of valley. Measurement of sinuosity, using even the conventional definition, is difficult due to variation in sinuosity with stage and discharge. Channel patterns can be characterized using the continuum approach primarily in a qualitative manner.

In both the quantitative threshold approaches and the more qualitative continuum method, "threshold" slope for braiding depends not only on discharge but also on bed and bank materials and other factors such as bank vegetation and valley confinement. Such thresholds may therefore vary between rivers, and over time in a single river. However, the direction of pattern response to change in the independent variables, discharge and sediment type, is predictable.

Valley Segment Classification

Another approach to classification, based upon the geometry of the valley where the channel flows, has been proposed by Cupp (1989). This valley classification uses valley morphology, channel pattern and position in the drainage network, and the nature of adjacent surfaces as a basis for defining units. While the approach includes information that makes it a more biologically useful tool for discriminating between channels, it is largely descriptive.

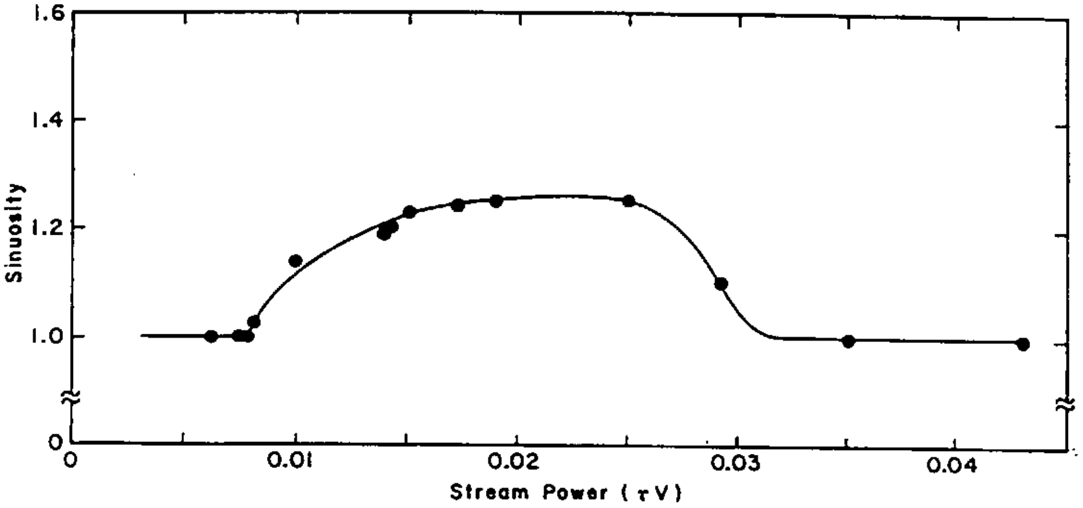


Figure 9. Schumm and Khan Continuum Approach.

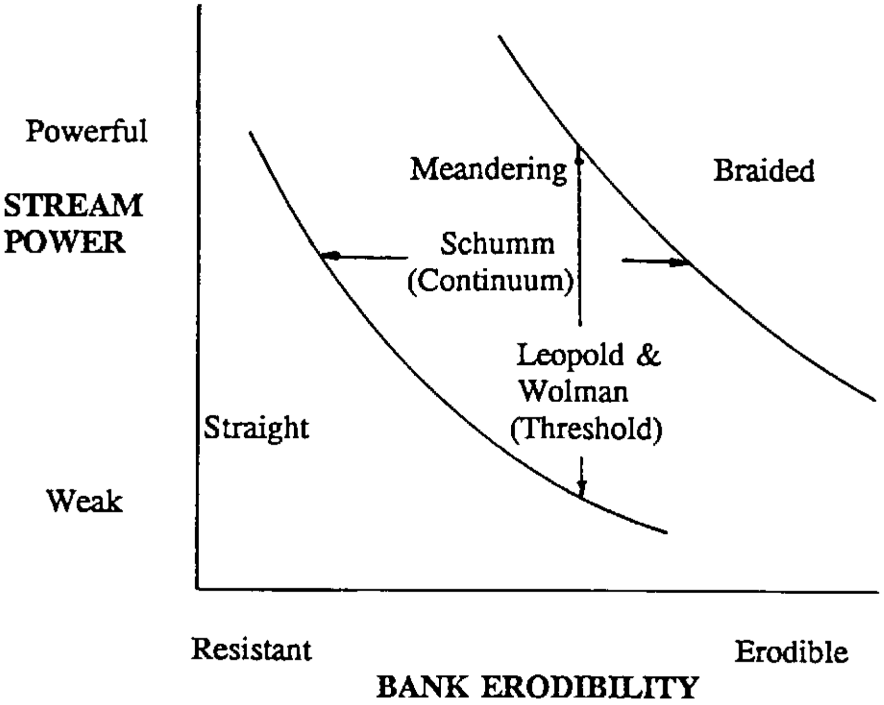


Figure 10. Comparison of Continuum and Threshold Methods.

Classification in Small Streams

Most of the aforementioned classification techniques were developed primarily for large alluvial streams, not for small streams such as those with which we are concerned. The properties of small streams and their sensitivity to forest practices are physically tied to basin hydrology, geometry and sediment sources. In contrast to larger channels, debris flows in smaller steeper basins contribute a substantial amount of sediment directly to the channel. Factors that are of importance in such systems include;

- bottom gradient as it affects shear stress potentially exerted and run-out distance of debris flows;
- sideslope gradient and length as they provide a source for debris flows;
- valley width as it determines stage-discharge relationships and isolates the channel from sideslope debris flows;
- substrate size and nature as it suggests sediment supply and potential for mobilization;
- stream structure as it suggests the role of LOD and/or bedrock obstruction in channel stability and resistance to flow;
- and vegetation type and density as it suggests the size, role, and nature of organic input to the channel.

The following section details the classification scheme we have developed for use in small streams.

SMALL STREAM CLASSIFICATION SCHEME

Presentation of Classification Scheme

The landuse manager needs a tool that identifies parts of the landscape in which various levels of protection should be applied in order to minimize or prevent environmental harm. Such environmental degradation might include, for instance, landslides, sedimentation, and downstream degradation of water quality. A tool to address these concerns is most valuable if the identification of landscapes is predicated upon a conceptual understanding of the physical, chemical, and biological processes that have shaped the earth surface and control its continuing evolution. Furthermore, such a tool is most useful if it incorporates this fundamental understanding in a quantitative manner. Only a classification scheme based upon a rigorous quantification of the most important processes controlling the movement of sediment in a drainage basin provides a framework for developing rational and appropriate land use regulations.

While such a tool must be scientifically sound, it is important that the classification scheme be sufficiently clear and simple that it can be applied by technical but non-expert staff. In the extensive but finite number of variables affecting landscape form and process, it is unreasonable to incorporate into a single scheme all possible conditions and scenarios that might influence landscape sensitivity. It is necessary to consider only those parameters fundamental to determining the parts of the landscape in which various processes are acting. The physical attributes that distinguish between landscape units of differing type must be easily measured in the field with a minimum of specialized training. These attributes might include key valley and channel dimensions, slope and the predominant sediment size. All of these variables are easily measured with a tape measure, stadia rod, level and ruler. It is probably counterproductive to have field staff make subjective decisions concerning the history of the basin or the mechanics of landslides, as part of the survey.

Furthermore, a tool of this sort should be adaptable to areas of varying hydrology, geology and history. While the universal application of such a tool may diminish it's site specific applicability, for purposes of screening, a generalized and accurate, if not precise, scheme is warranted. For example, if a forest manager is planning to site a road on a steep slope, it would be prudent to investigate the hillslope stability in detail in relation to the local soil properties including soil depth, degree of saturation, hillslope convergence, internal angle of friction, building surcharge, and seismic acceleration. If on the other hand a forest planner is surveying a large area for a hazards zone delineation or for delineation of environmentally sensitive areas, such a detailed approach is beyond the appropriate scope and effort for the purpose at hand.

A number of classification schemes to describe types of rivers or valleys have been developed and these were presented in the previous section. These schemes have generally been oriented to and appear biased toward larger rivers and valleys where alluvial processes predominate. However, for many problems confronting the land manager, it is for the finer scale of the drainage network that a classification scheme would be most useful. In such regions, hillslope processes and primarily debris flows are a significant agent in the flux of material into and through the drainage network. Other classifications do not differentiate between channels or valleys on the basis of this change in process, or in the way and degree to which landscape disturbance is likely to cause environmental degradation. In addition, previous classification attempts were more subjective and arbitrary in the partitioning of variable-space; that is to say artificial boundaries between different types of channels were created without regard to the primary differences between parts of the landscape, and the importance of the various processes.

A classification scheme is presented in this section which is predicated upon differentiating between the importance of various geomorphic processes in transporting material into and through the channel network. The domains in which various processes are thought to be predominant correspond to the different stream types. The scheme is both logical and rational and can be taught easily to technical staff giving a minimum of subjective variability. The scheme is broadly applicable in the State of Washington. The variables thought to describe the processes generating sediment and controlling the potential for environmental degradation are easily measured in the field. These variables are hillslope gradient, channel gradient, valley bottom width, channel width, channel depth and sediment size.

Hillslope gradient determines, in large part, the stability of a surface and the likelihood of failure by landslide. A common method in engineering for describing hillslope stability is to apply a factor of safety analysis (Terzaghi and Peck, 1967).

$$F.S.=\frac{C+(\rho_s-m\rho)zg\ \cos\ \theta\ \tan\ \varnothing}{\rho_s\ zg\ \sin\theta} \qquad (1)$$

ρ_s and ρ are the sediment and fluid density, g is the acceleration of gravity, z is the soil thickness above the potential failure plane, m is the proportion of the soil depth that is saturated, θ is the hillslope angle, $\varnothing$ is the internal angle of friction, and C is the cohesion provided by moisture, roots, or soil composition. The factor of safety defines the ratio of the strength of a soil to the gravitational forces driving movement. A factor of safety greater than 1.0 means that the soil strength provided by the friction due to the soil weight and any cohesion in the soil exceeds the gravitational stress on the slope and implies that landslides are unlikely. Conversely, a factor of safety less than 1.0 implies that the slope is unstable. For cohesionless soils with a conservative internal angle of friction of 27° (Terzaghi and Peck, 1967), assuming the soil is completely saturated, the factor of safety (F.S.) can be written as

$$F.S.=\frac{1}{1.66\ \tan\ \theta} \qquad (2)$$

Rearranging terms, 1/F.S. = 1.66 tan θ or 1/F.S. = 1.66 S_s where S_s is the hillslope gradient.

Channel gradient is a fundamental factor in determining the gravitational force acting to move water and sediment. Benda and Cundy (1990) found that coarse textured debris flows in the Pacific Northwest tend to scour, often to bedrock, channels with slopes greater than 10^0

(17%). Debris flows tended to deposit in less steep channels. Debris flow runout and hence debris flow deposition generally ceased by the point stream gradients dropped below 3.5^0 (6%). Other workers report slopes in the downstream parts of debris flow depositional areas of $4\text{-}10^0$ (Pierson, 1980), $3\text{-}10^0$ (Ikeya, 1981), and $3\text{-}5^0$ (Mizuyama 1981). Calculations of stability suggest that in some settings the axes of some drainages may be sufficiently steep to be the sites of failures themselves (Ashida, 1987). Corroborating reports of such in-channel failures are rare.

In primarily clear water flows, the gravitational force per unit area acting to move water and sediment is written as

$$\tau_b = \rho g H S \tag{3}$$

The total boundary shear stress is $\tau_{b,}$ ρ is the fluid density, g is the gravitational acceleration, H is the bankfull channel depth, and S is the channel gradient. The steeper the channel slope, for the same flow depth, the greater the force applied to the channel bottom, hence the greater the capacity and size of material carried by the fluid.

Valley width controls the hydrologic regime and whether debris flows coming off of the adjacent slopes enter streams in the valley bottom. Valley width is defined as the distance between facing valley side slopes, measured at the break in slope to the relatively flat bottom of the valley. Depending upon the size, fluidity, and speed of the debris flow, the mass will travel a varying distance over the relatively flat valley bottom before friction, in the absence of sufficient driving force, leads to deceleration and stoppage of the debris flow. Standing trees and logs act to slow the flow. If the valley is sufficiently narrow, debris flows will enter the channel directly, whereas if the valley is sufficiently wide, the debris flow will come to rest on the valley bottom without directly entering the channel. In the first case, the hillslope processes are directly coupled to the channel processes while in the second, the hillslope processes are largely de-coupled from the channel processes.

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Ikeya (1981) inventoried debris flows in Japan and found empirically that the length they travel before deposition can be related to the initial volume of the flow and the slope of the depositional surface. For landslides with an initial volume of 500 cubic meters, approximately the volume Benda (1990) estimated in the Oregon Coast Range before flows entrained channel sediments, the Ikeya method would predict a depositional length of 25 meters with the depositional surface slope of 0.05. This indicates that a valley bottom width (measured from one side of the valley across the valley to the break in side slope) greater than 25 meters for this size landslide limits direct debris flow contributions to the channel network.

Channel width is the other indicator of the degree to which the hillslope contributes material directly to the channel. The amount of valley bottom occupied by the channel itself is basic to the amount of channel-hillslope interaction. A very wide valley bottom, but one entirely taken up by the channel, will not have a valley flat on which to trap sideslope debris flows. The valley aspect ratio, valley width as compared to channel width, also plays a role in the purely alluvial part of the system. A wider valley bottom tends to diminish flood heights because of the greater flow area, buffering against extreme discharge events. Channels in such settings are more likely to be dynamically stable and to have a characteristic geometry. Floods in narrow valleys will cause proportionately larger stresses than those in wider valleys as a result of greater depth of flow and these channels will be less regular in their form.

Channel depth along with channel slope, through the downslope component of the weight of the fluid, determine the force applied per unit area on the channel. The shear stress is what ultimately mobilizes sediment and hence creates characteristic topography. In many settings, this characteristic topography is linked to recurring flows. In this way, characteristic geometry can be used to anticipate the characteristic discharges and depths which have historically built these channels. Average channel depth multiplied by the downslope component of the

$$\theta = \frac{\rho g H S}{(\rho_s - \rho) g D_{50}} \qquad (4)$$

The dimensionless coefficient has a value at initial motion of 0.03. ρ and ρ_s are, respectively, the fluid density and density of sediment, g is the acceleration of gravity, H the flow depth, S the channel slope, and D_{50} the median bed sediment size. It has been assumed that all the shear stress is applied directed to the sediment particles with no resistance imparted by other channel form features. If the stresses just exceed the threshold for motion, particles roll. As stresses are raised, progressively more and larger sediment hops into the flow (saltates). At yet greater shear stresses, grains may be swept off the bed and move suspended in the flow. It has been found that an approximate criteria for suspension is that the downward velocity of a sediment particle settling in water must be less than the square-root of the applied shear stress (McQuivey and Richardson, 1969).

$$w_s \leq \sqrt{\frac{\tau_b}{\rho}} \qquad (5)$$

The median size of sediment in the channel determines the rate at which it moves, how frequently it may move, and the process by which it moves; bedload (rolling, saltation), or suspension. Grain size also seems to control geometric properties of the channel. When the predominant sediment size is cobbles and boulders, spanwise cascades and riffles are found in the channel. Rarely are other bed features noted. Often finer sediment collects in the pools behind the cascades (Grant et al., 1989). Fine gravel to fine cobble channel surfaces are often dynamically armored in that they possess a coarse surface layer distinct from the finer substrate. Armoring, sometimes called paving, has rarely been observed at shear stresses that are more than a factor of three greater than the critical shear stress for initiating sediment movement. Dynamic armoring can occur in cases where sediment supply has been reduced as a whole or locally across the channel (Dietrich et al., 1989). In such settings an armor can be interpreted to suggest the capacity of the channel to carry more sediment. A channel with a strongly armored surface can carry additional sediment without aggradation but it will become finer, whereas an unarmored channel is probably transporting sediment at or near its limit and additional supply is likely to cause aggradation. Armoring does not occur in sand bed streams. Sand bed channels typically have a variety of superimposed bedforms including dunes and ripples. Channel pools and bars are usually well developed. In such streams the resistance to flow generated by the growth of these bedforms can be substantial and this acts to reduce the portion of the total boundary shear stress available for moving material. Correction of the stress to account for this effect was not attempted given the more general nature of the results we seek.

Silt and finer sediments are usually found in deep channels with well defined banks and are uncommon in upland streams except locally in aggrading, flatter meadows typically upstream of valley constrictions. Such material commonly moves as suspended load and these sediments are transported quickly and in large volumes to downstream areas. Finer sediment derived from landuse tends to be a major problem for the manager because these sediments are those primarily responsible for water quality and fisheries degradation, especially downstream of the source. Larger clasts including gravel and cobbles can be detrimental if deposited in large quantities. Such deposits can effect stream channel geometry, and sedimentation processes.

A process-based classification scheme for use in small streams in the State of Washington based upon the concepts and variables outlined above is presented in Figure 11. The classification assigns an alphanumeric code to channels likely to behave in a similar manner because of similar processes and morphology. The first part of the code classifies the potential of hillslopes and the valley to contribute material to the channel while the second part of the code classifies the potential of the channel to move this material downstream. The distinctions made between types of streams (the term stream is meant to include the channel and its setting in a valley with contributing hillslopes) have been made at meaningful places where, because of physical differences, there is a change in process. To the degree possible, arbitrary partitioning of the physical properties has been avoided. In other words, the classification scheme is a map of the domain of different and distinct physical processes and their relative rates, rather than a in a valley with contributing hillslopes) have been made at meaningful places where, because of physical differences, there is a change in process. To the degree possible, arbitrary partitioning of the physical properties has been avoided. In other words, the classification scheme is a map of the domain of different and distinct physical processes and their relative rates, rather than a

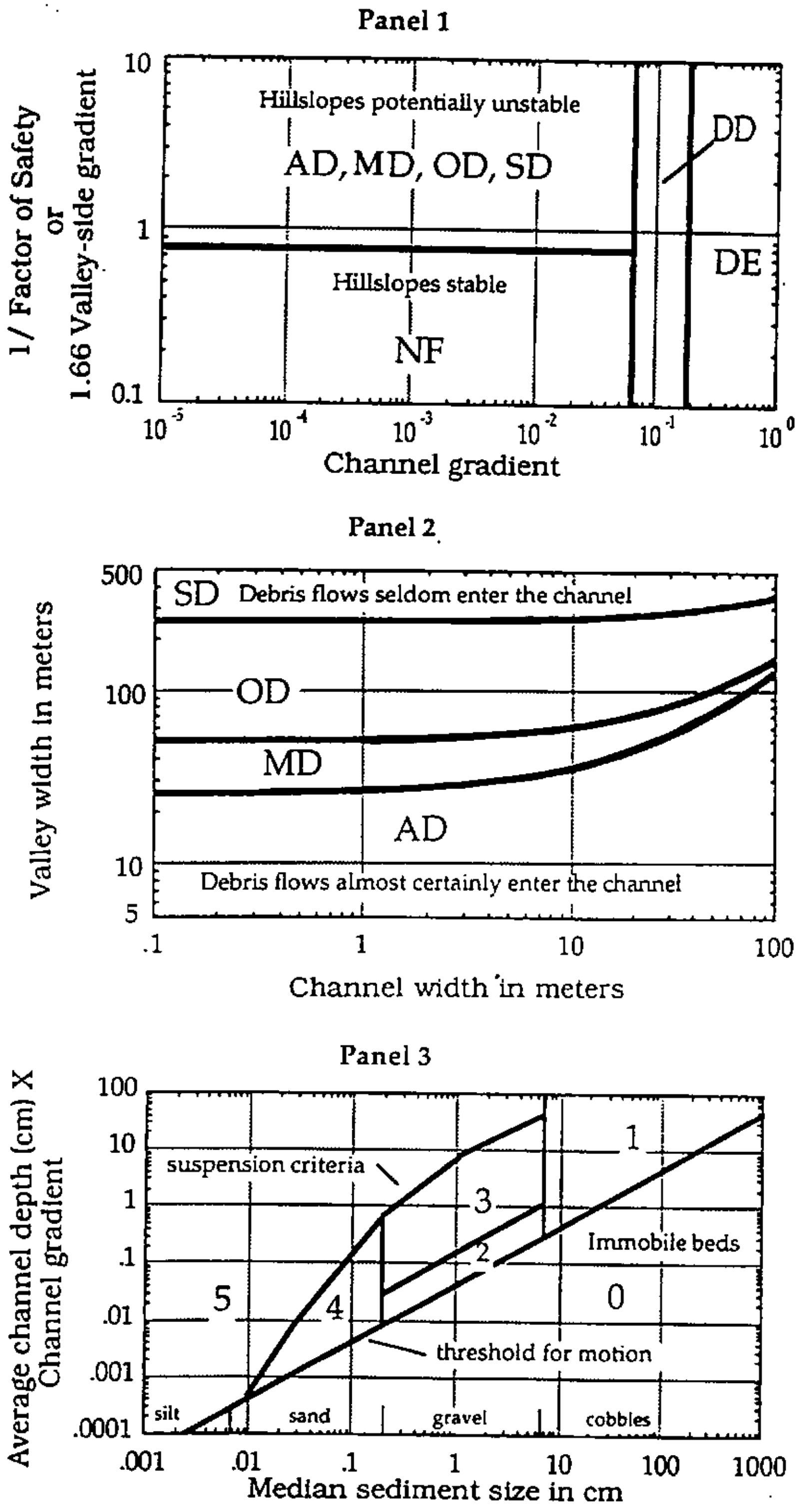

Figure 11. Recommended Small Stream Classification.

map of relative size or subjective stability.

There are three panels presented in Figure 11 to define stream type. The first panel has an abscissa of channel gradient, and an ordinate that can be portrayed as either $1.66S_s$ or 1/F.S. These are equivalent values for typical conditions listed earlier. This first panel is broken into four domains; an area DE where the channel is steep enough that valley bottom debris flows erode channel sediments (channel slopes greater than 10^0- gradients steeper than 0.17), an area DD where channel gradient is less steep so that debris flows are transported through the reach or deposit material in the channels as they runout (channel slopes of 3.5 to 10^0 - channel gradients of 0.06 to 0.17), an undifferentiated area including SD, OD, MD, and AD where the channel itself is insufficiently steep to transport debris flows, but where adjacent hillslopes are prone to landsliding, and an area NF where the adjacent hillslopes are not susceptible to landsliding. The delineation between such fields is at an ordinate value of 0.80, which to be conservative has been reduced from the 1.0 value expected when stabilizing forces just balance driving forces. The dual ordinate is designed for two very different situations. In one set of circumstances a great deal of information is known about the particular conditions of the slope; the degree of saturation, the bulk soil properties, and the cohesion provided by roots, structures, soil forces, or the collection of such detailed information is warranted by the sensitivity of the area. On the other hand there may be circumstances where little is known except hillslope gradient and there is little need or possibility for more detailed information. When detailed information exists, or can be collected, a full analysis can be done and 1/F.S. can be used; when little is known, $1.66S_s$ is used. For typical conditions at failure-no cohesion, complete saturation of the soil column and an internal angle of friction of 27°, the two labels give an identical answer. If there is physical evidence of landslides on hillslopes, slopes should be catalogued as unstable in spite of calculations to the contrary. Conversely, the lack of such evidence should not be taken to suggest stability of hillslopes if calculations suggest otherwise.

The second panel further distinguishes between stream systems by examining the valley aspect to indicate the effects it might have mediating hillslope processes and buffering large erosive floods. This panel is to be used for differentiating between the SD, OD, MD, and AD channels clustered together in the upper half of the first panel. The abscissa is channel width taken at the top of the banks (bankfull width) or at a characteristic discharge, and the ordinate is the valley width taken as the distance between opposing valley hillslopes, at the base of those slopes. This panel is broken into four domains separated by three approximately parallel curves. If the valley bottom is narrower than the sum of the channel width plus the estimated debris flow deposition length of 25 meters, a sideslope debris flow will almost certainly enter the channel. Even if the channel flows along the base of the hillslope opposite to the destabilized slope, the valley bottom is insufficiently wide in this case to trap the debris flow and debris flow material almost assuredly enters the channel. Such valley bottoms are coded as AD. Another process, the "dambreak flood" (Benda and Zhang, 1989) has been documented to occur in AD streams. Landslides or debris flows can plug valleys narrower than approximately 25 meters (Coho and Burgess, 1991) subsequently ponding water upstream which eventually overtops the deposit and breaches the "dam". In wider valleys, fewer sideslope debris flows reach the channel. There is a 50% chance that a valley whose width is equal to the sum of the channel width and 50 meters (a depositional length of 25 meters on each side of the channel) will have debris enter the channel. The estimated probability can be understood with the realization that a channel does not flow everywhere along the center of the valley. Along approximately 50% of the valley, the channel is to one side of the valley centerline and in this area the valley floor is locally too narrow to trap debris. This calculation assumes that the channel can occupy any point within the valley flat and that there is no spatial bias in the position of the channel within the valley. Similarly, there is a 10% chance that a valley whose width is equal to the sum of the channel and 250 meters (four depositional lengths) will have debris flows enter the channel. Valleys in which most sideslope debris flows enter the channel (with a probability of 50-100%) are coded as MD; valleys in which the channel occasionally receives sideslope debris flows (with a probability of 10-50%) are coded as OD; and valleys in which the channel seldom receives sideslope debris flows (with a probability of less than 10%) are coded as SD.

The first two panels lead to the assignment of a double letter prefix to describe the valley setting, specifically the propensity for having sideslope landslides that carry material into the channel. The third panel describes the alluvial processes that often determine the local and downstream effects of land use. The abscissa is the median grain size of the bed surface layer in the channel or as exposed on the tops of channel bars. The ordinate is the product of channel slope and the average channel depth under formative conditions. This is usually taken as the bankfull level where water is just spilling out of the banks. This plot is a thinly disguised variation plot of the Shields diagram (Equation 4) which relates the fluid forces causing sediment motion to gravitational forces. It has been assumed that the fluid and sediment have densities of 1.0 and 2.65 grams/cubic centimeter, respectively. Further, it has been assumed that the total boundary shear stress is approximately the stress applied to bed sediment particles, and flow resistance due to channel form and bedforms is minor. There are six domains on this panel; area 0 represents situations in which the sediment is likely to remain immobile in all but the most extreme events, area 1 where sediment is above the criterion for motion and the grain size is cobbles and larger (coarser than 6.4 cm), area 2 of fine gravel to cobbles where the grains are potentially mobile and the bed is typically armored but shear stresses are never greater than 3 times the threshold for incipient motion, area 3 of fine gravel to cobbles where the shear stresses are substantially above critical and surface armoring is unlikely, area 4 of primarily sand sized material where sediment is transported as bedload, and area 5 where sediment is fine or stresses very high and material moves primarily in suspension.

The alphabetic and numeric codes are combined to give the stream classification. For instance, a drainage with sideslope gradients of 0.10 (10%), a valley width of 25 meters, a channel width 10 meters, a depth of 1 meter, a channel gradient of 0.004, and a median grain size of bed material of 1 cm is classified as an NF3 stream. The NF3 code would signify that mass wasting processes were rather unimportant in this basin because of gentle slopes despite a narrow valley width, and that the gravel channel bed had stresses that were a factor of 3 greater than necessary to move the bed sediment. Material moves primarily as bedload and armoring is not present. Another example is for a drainage where the sideslopes have a gradient of 0.50, but an engineering analysis considering the degree of soil saturation gives an unstable value of 0.83, the channel slope is 0.02, the valley width is 30 meters, channel width and depth are 3 meters and 50 cm, respectively, and the median bed material size is 10 cm (cobbles); the stream is classified as a MD1 channel. The MD1 code signifies that valley side slopes are sufficiently steep to generate debris flows of which some will enter the cobble-bedded channel.

A summary of the salient geometric and hydraulic variables used to reach a classification are given in Table 3. Table 4 describes how each type of channel may respond to several recognized environmental concerns associated with land use e.g. -and sedimentation, fine sediment intrusion, as it effects fisheries water quality degradation. In general, several qualitative estimates can be made. Steeper channels are most likely to pass debris flows or otherwise to rapidly carry debris downstream. Finer bed channels indicate that fine material is common and likely to represent a substantial part of the load. If a small channel is fine bedded well upstream it can be assumed that there is a substantial supply of fines and that the fines will be common, and problematic downstream. The higher the transport stage (the stress relative to that needed to initiate particle motion), the more quickly the effects are felt downstream as material is carried more frequently in suspension. The more rapid the downstream migration of debris, the less likely are opportunities for storage in the valley bottom. Wider valleys are less likely to have sideslopes contributing large amounts of material to the channel and wider valleys have substantial areas in which to store influxes of material potentially associated with landuse change.

Application of the Classification Scheme

The use of this classification system for evaluating the type of small stream and therefore estimating the potential local and downstream impacts of land management decisions depends upon careful field measurement of the physical quantities used to identify these streams. The most appropriate application of this classification system involves on-the-ground surveys of basins to categorize individual reaches along the drainage. Individual reaches so classified might be on the order of tens to hundreds of meters long depending upon the size of the drainage. For some purposes, a much coarser general screening can be made and entire first-order basins given an average classification. Conversely, for special circumstances, perhaps near a critical site or in very sensitive areas, the resolution might be increased to look at even smaller units only meters or tens of meters across. A stream may locally abut a steep slope in an otherwise very wide valley such that prudence would suggest avoiding significant disturbance just upslope, while in the remainder of the drainage hillslope contributions are minor. The intermediate scale of

Stream class	Channel/hillslope susceptibility to landslides	Valley aspect	Channel description
DE0	eroding in-channel debris flows	typically narrow	debris chute often on bedrock
DE1	"	"	scoured bouldery debris chute, w/LOD?
DE2	"	"	scoured bouldery debris chute, w/LOD?
DE3	"	"	****
DE4		"	****
DE5	"	"	****
DD0	depositing in-channel debris flows	typically narrow	debris chute
DD1	"	"	bouldery debris chute w/LQD
DD2	"	"	aggrading gravelly debris chute w/LOD
DD3	"	"	****
DD4	"	"	****
DD5	"	"	****
AD0	adjacent hillslopes prone to failure by debris flow / "	very narrow: VW - CW < 25 m	immobile, ephemeral
AD1		"	bouldery cascades
AD2	"	"	armoured gravel
AD3	"	"	no armour, T > 3 Tcr
AD4	"	"	sandy, bedload predominant
AD5	"	"	silty, suspended load channel
MD0	"	narrow: 25 m < VW - CW < 50 m	immobile, ephemeral
MD1	"	"	bouldery cascades
MD2	"	"	armoured gravel
MD3	"	"	no armour, T > 3 Tcr
MD4	"	"	sandy, bedload predominant
MD5	"	"	silty, suspended load channel
OD0	"	moderate: 50 m < VW - CW < 250 m	immobile, ephemeral
OD1	"	"	bouldery cascades
OD2	"	"	armoured gravel
OD3	"	"	no armour, T > 3 Tcr
OD4	"	"	sandy, bedload predominant
OD5	"	"	silty, suspended load channel
SD0	"	wide: VW - CW > 250 m	immobile, ephemeral
SD1	"	"	bouldery cascades
SD2	"	"	armoured gravel
SD3	"	"	no armour, T > 3 Tcr
SD4	"	"	sandy, bedload predominant
SD5	"	"	silty, suspended load channel
NF0	hillslopes stable	variable, often narrow	immobile, ephemeral
NF1	"	variable, often narrow	bouldery cascades
NF2	"	variable	armoured gravel
NF3	"	variable	no armour, T > 3 Tcr
NF4	"	commonly wide	sandy, bedload predominant
NF5	"	commonly wide	silty, suspended load channel

CW = channel width
VW = valley width

**** = rare, unlikely
T = boundary shear stress
Tcr = T at initial motion

Table 3. Geometric and Hydraulic Variables.

Table 4. Environmental Sensitivity.

Stream class	Sedimentation	Fine sediment intrusion	Water quality degradation
DE0	Frequently scoured debris chutes continually accumulate colluvium; biggest problems are downstream with failure of this material	Locally may be important if basin sediment is fine. Otherwise, rather unimportant on often scoured bedrock.	In its present condition, may not contribute significantly to turbidity.
DE1	Boulder lag receives hillslope colluvium and LOD clogging drainages. Often stepped profile with sediment collecting in lee of LOD, boulders.	Locally may be important. Accumulation behind steps in profile.	Preponderance of coarse material implies minor contribution to turbidity, but major if debris flow triggered.
DE2	Gravelly fills may imply that debris chute has accumulated much material. If this fails, large sedimentation problem downstream.	Fines may accumulate, then flushed downstream in larger discharges.	Preponderance of coarse material implies minor contribution to turbidity, but major if debris flow triggered.
DE3	Probably rare, but the high shear stresses imply that material is easily moved out of the local reach.	Fines likely to be swept downstream in suspension, so local intrusion minor.	Preponderance of coarse material implies minor contribution to turbidity, but major if debris flow triggered.
DE4	Probably rare. Sand size material suggests that material is easily moved out of the local reach. Problematic downstream?	If bed is sandy, likely that there will be accumulation of fines.	Fine material implies may be source of some turbidity, will be exascerbated if material incorporated in debris flow.
DE5	Probably rare, but where found implies basin easily eroded and likely to be very prone to sedimentation.	Bed is fine, thus intrusion of fines has little significance.	Fine material may add to debris flow material to be major source of turbidity.
DD0	Decreasing channel slope causes upstream debris flows to deposit. Sedimentation significant. Material persists since tractive force available.	Deposited fines are unlikely to be removed since stresses low.	Even though stresses may not mobilize majority of the bed, fines may be flushed increasing turbidity.
DD1	There is likely to be substantial accumulation of material. Removal of coarse fraction is slow. Mainly local effects.	Local effects probably minor by flushing associated with scour around large debris and generally coarse size.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
DD2	Debris flow material may persist since relatively coarse material and marginal stresses. Bedload stream. Effects somewhat local to deposit area.	Fines likely to infiltrate bed quickly after flushing given likely large availability.	Preponderance of coarse material implies minor contribution to turbidity but major if debris flow triggered.
DD3	Relatively high shear stresses imply that material will be relatively quickly transported downstream by the channel.	Infiltration likely but more frequent scour should speed up gravel recovery; fines are passed downstream quickly.	Higher stresses may flush fines in the short term increasing turbidity, but in the long term quick recovery.
DD4	Sandy debris flow deposits will be transported easily so while rapid recovery, local and downstream effects.	Infiltration of fines will be common given large availability. Since material so mobile effects well downstream.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
DD5	Fine debris flow deposits imply rapid removal, but effects extending well downstream with suspension.	Fine intrusion into bed.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.

Table 4. Environmental Sensitivity.

Stream class	Sedimentation	Fine sediment intrusion	Water quality degradation
AD0	Side-slope debris flows will almost certainly enter the channel, and low stresses will prevent local removal; only fines carried downstream	Fines in the debris flow deposit will be winnowed: these likely to intrude the channel bed downstream	Low stresses may limit turbidity.
AD1	Side-slope debris flows will almost certainly enter the channel; local and downstream aggradation	Winnowing of fines with local deposits esp. in backwaters of cascades, much of the fines swept downstream.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
AD2	Debris from sideslope is slowly reworked. Large sediment supply may limit formation of a armour that would otherwise limit erosion.	Reworking of debris is a persistant source of fines that may be problematic downstream. Supply may limit armour.	Preponderance of coarse material implies minor contribution to turbidity
AD3	Greater stresses may shorten time span of removal of debris. Relatively energetic stream will sweep wave of sediment downstream.	Greater stresses may limit the amount of local fine intrusion, but narrow valley transports effects well downstream	Higher stresses may flush fines in the short term increasing turbidity.
AD4	Sand is relatively rapidly evacuated from local reaches, but wave of sediment sweeps well downstream.	With fines making up a substantial part of load, embeddedness common along the channel length.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
AD5	Rapid local evacuation of fine material with suspension, substantial aggradation downstream may be limited by easy entrainment	With source of fines the downstream reaches will receive constant flux. Expect complete embeddedness.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
MD0	Most side-slope debris flows enter the channel, and low stresses will prevent local removal; only fines carried downstream	Fines in the debris flow deposit will be winnowed: these likely to intrude the channel bed downstream	Low stresses may limit turbidity.
MD1	Most side-slope debris flows enter the channel, with local and downstream aggradation.	Winnowing of fines with local deposits esp. in backwaters of cascades, much of the fines swept downstream.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
MD2	Debris from sideslope is slowly reworked. Large sediment supply may limit formation of a armour that would otherwise limit erosion.	Reworking of debris is a persistant source of fines that may be problematic downstream. Supply may limit armour.	Preponderance of coarse material implies minor contribution to turbidity
MD3	Greater stresses may shorten time span of removal of debris. Relatively energetic stream will sweep wave of sediment downstream.	Greater stresses may limit the amount of local fine intrusion, but narrow valley transports effects well downstream	Higher stresses may flush fines in the short term increasing turbidity.
MD4	Sand is relatively rapidly evacuated from local reaches, but wave of sediment sweeps well downstream.	With fines making up a substantial part of load, embeddedness common along the channel length.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
MD5	Rapid local evacuation of fine material with suspension, substantial aggradation downstream may be limited by easy entrainment	With source of fines the downstream reaches will receive constant flux. Expect complete embeddedness.	Even if debris is trapped on the valley flat, can expect downstream turbidity in short-term as muddy water delivered.

Table 4. Environmental Sensitivity.

Stream class	Sedimentation	Fine sediment intrusion	Water quality degradation
OD0	Side-slope debris flows occasionally enter the channel in wide valley, sedimentation common in these areas since poor channel capacity	Importance of fines strongly linked to number of debris flows. Downstream effects limited by floodplain storage.	Low stresses and deposition on valley floor limit turbidity.
OD1	Some side-slope flows enter the channel in wide valley, sedimentation is local and concentrated behind cascades.	Intrusion of fines temporally and spatially driven by occasional debris flows. Raw banks as important.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
OD2	Sediment storage on valley flat limits aggradation. Coarse surface may disappear in short-term as load increased with debris flow input.	Intrusion of fines temporally and spatially driven by occasional debris flows. Raw banks as important.	Preponderance of coarse material implies minor contribution to turbidity
OD3	Greater stresses shorten time span of debris removal. Relatively energetic stream and wide will diffuse wave of sediment rapidly.	Fine intrusion limited except in local backwaters, and downstream of fine source - raw bank, tributaries.	Higher stresses may flush fines in the short term increasing turbidity.
OD4	Sand is rapidly evacuated from local reaches, and with valley floor storage, downstream effects of occasional debris flow are limited.	With fines making up a substantial part of load, embeddedness common along the channel length.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
OD5	Rapid local evacuation of fine material with suspension, aggradation downstream minimal with easy mobility, sites for off channel storage.	With fines making up most of the load, embeddedness is common along much of the channel length.	Even if debris is trapped on the valley flat, can expect downstream turbidity in short-term as muddy water delivered.
SD0	Side-slope debris flows rarely enter the channel in the wide valley, sedimentation likely anyway in these areas since poor channel capacity.	Fine intrusion governed by local flushing of fines from the channel.	Low stresses and deposition on valley floor limit turbidity.
SD1	Rarely side-slope flows enter the channel in wide valley, sedimentation is local and concentrated behind cascades.	Intrusion of fines locally in areas of quiet water. Source of fines includes debris flows, raw banks, disturbance.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
SD2	Sediment storage on valley flat limits aggradation. Coarse surface may disappear in short-term as load increased with debris flow input.	Intrusion of fines locally in areas of quiet water. Source of fines includes debris flows, raw banks, disturbance.	Preponderance of coarse material implies minor contribution to turbidity.
SD3	Relatively energetic stream confines aggradation to local reaches. Channel may be more prone to incise.	Fine intrusion limited except in local backwaters, and downstream of fine source - raw bank, tributaries.	Higher stresses may flush fines in the short term increasing turbidity.
SD4	Channel is probably fairly stable, aggradation is limited to local reaches responding to rare debris flows or changes in baselevel, LOD.	With fines making up a substantial part of load, embeddedness common along the channel length.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
SD5	Sedimentation is locally driven by rare debris flow input, other sources of sediment - raw banks, road wash, valley floor disturbance.	With fines making up most of the load, embeddedness is common along much of the channel length.	Fine bed implies turbidity associated with any flows, may be exascerbated by disturbance in the watershed.

Table 4. Environmental Sensitivity.

Stream class	Sedimentation	Fine sediment intrusion	Water quality degradation
NF0	Stable side slopes, butvariable valley aspect suggest sedimentation governed by amount of colluvial input.	Fine intrusion governed by local flushing of fines from the channel.	Low stresses and deposition on valley floor limit turbidity.
NF1	Stable side slopes; long-term aggradation likely in wide, gently sloped valleys, aggradation driven by hydrologic regime, basin disturbance.	Intrusion of fines locally in areas of quiet water. Source of fines includes debris flows, raw banks, disturbance.	Preponderance of coarse material implies minor contribution to turbidity except as fines flushed.
NF2	Stable side slopes; long-term aggradation likely in wide gently sloped valleys, aggradation driven by hydrologic regime, basin disturbance.	Intrusion of fines probably depends upon on frequency of armour breakup.	Preponderance of coarse material implies minor contribution to turbidity
NF3	Stable side slopes; long-term aggradation likely in wide gently sloped valleys, aggradation driven by hydrologic regime, basin disturbance.	Fine intrusion limited except in local backwaters, and downstream of fine source - raw bank, tributaries.	Higher stresses may flush fines in the short term increasing turbidity.
NF4	Stable side slopes, long-term aggradation common in wide valleys; in narrow valleys may occur with basin disturbance.	With fines making up a substantial part of load, embeddedness common along the channel length.	Fine material implies a major source of turbidity, flushed downstream rapidly and even at lower discharges.
NF5	Stable side slopes - sedimentation probably governed by basin disturbance including fire.	With fines making up most of the load, embeddedness is common along much of the channel length.	Fine bed implies turbidity associated with any flows, may be exascerbated by disturbance in the watershed.

resolution is probably most useful for it approaches the size of the elements associated with land management, for example road widths, riparian management zones, and clearcuts.

The measurement of physical quantities and the mapping of stream types should take place in the field. Technical teams with two or three members should walk the length of the basin assigning a class to stream-valley segments at a chosen interval, or where classes change. The location and class of each segment should be recorded on a map. It is recommended that the measurement values be recorded in order to justify assigned classes, to modify designations if the classification system is refined, and to provide a baseline for longterm studies. In addition it is useful to note the plotting position of sites on the different panels of Figure 11 in order to be aware how close the site is to another channel class. In some settings it may be prudent to assign the proper class but to note that the segment is sufficiently close to another class that more stringent regulations appropriate to this second class should be applied.

Measurements of channel and hillslope gradients should be made with a surveying level and stadia rod. In many settings, the brushiness or the ruggedness of the topography may make such surveying difficult. In such cases a careful measurement of slope with a hand-held level and a stadia rod may give accurate enough information for classification. Nonetheless, it is preferable for channel slope to be measured with a surveying level. Valley bottom width and channel width should be measured with a tape measure if at all possible. After some practice, estimated distances might be acceptable in rugged or very wide conditions. Valley width is the distance between the base of the adjacent hillslopes. Average channel depth is the depth from the top of the banks and should be determined from measured stream cross-sections. Median grain size of the channel bed surface material should be determined from measurement of the intermediate axis of the representative grain size. Measurements should be made in a systematic way in the channel such as the top of emerged bars. A pebble count of 50-100 bed surface grains is recommended, following the methodologies presented by Dunne and Leopold (1978).

Discussion

The basis of this classification scheme is the logical partitioning provided by a change in geomorphic process. Past schemes have tended to describe and inventory streams rather than understand how they function and thereby use this knowledge to structure a perspective of the landscape. It matters little whether two valleys and streams may be of similar size and appearance, the landuse manager wants, and in fact, needs to know, if they will respond in a similar manner to various landuse practices. If two classified areas based upon their response are judged similar, then they warrant a similar set of rules and regulations to minimize local and off-site environmental degradation. Consistently in this scheme, delineations have been made wherever possible on the basis of known changes in process. For example, though the boundary of the domain in which armoring occurs appears somewhat arbitrary, armoring has been observed primarily in gravel (2-64 mm). While there is certainly a physical reason for this, probably tied to the modes of motion and to relative sediment sizes, a more precise physical criteria other than grain size is unavailable at this point. Admittedly, close to arbitrary ratios of scale were applied in considering the effect of valley aspect (i.e. 10-50% probability of debris input). These continue to be examined by researchers and a refined estimate of geometric properties may be possible in the future. In all other respects, the boundaries delineated are based on understanding of the physical process as presented earlier.

The application of this general classification scheme to the various physiographic regions of the State of Washington is an issue raised by some members of the forestry and geologic communities. There are two reasonable approaches; 1) a single classification scheme with regional regulations that take into account local hydrology, geology, and basin condition, or 2) a classification for each region that itself tries to account for variation in these local conditions. The authors' preferred choice is the single classification for small streams using local regulations. The reasons for this are many. First, while the demarcation between domains might be shifted to be more conservative in one region as compared to another, the knowledge base is sufficiently tenuous to make such a procedure suspect. Secondly, an MD1 channel for example, should be recognizable and a consistent landscape unit that is independent of region.

Third, processes do not change fundamentally across the physiographic regions of Washington, it is the frequency of occurrence that changes. A hillside that is sufficiently steep and wet can generate debris flows whether or not it is in one region or another; what varies is the likelihood and frequency. It seems to us that it is more appropriate to have a system that identifies potential for such processes while local regulations address the importance of such possibilities from the perspective of the landuse manager. Finally, this report represents a first attempt to structure a meaningful process-based scheme and it seems most relevant to focus on the basic conceptual framework rather than addressing subtle shifts in class boundaries. Despite these statements, if it becomes necessary to develop regional relations, a logical point to vary a scheme by region is in terms of the ordinate on the second panel which represents the Factor of Safety and likelihood of mass-wasting processes. A shift in the degree of conservatism could be used to account for the greater frequency of such catastrophic events in some regions.

Some variables that are significant in the susceptibility of an area to degradation with landuse change are not included explicitly in this classification scheme. Several of these are hydrology, basin condition, and the role of large organic debris. In some sense hydrology is incorporated implicitly in terms such as the width and depth of the channel. Both of these quantities are highly correlated to runoff. Other important variables such as organic debris are not included because they are not at this stage of our knowledge logically connected to the other physical attributes in a systematic manner. Other variables such as basin condition are transient and the role basin condition plays might best be treated in another manner, possibly with another classification scheme that treats this issue and perhaps large organic debris as well. The classification scheme proposed herein is meant to be fairly invariant in human time scales. Basic geometric properties are unlikely to be changed over such a short time span. Periodic visits to update the stream type should be unnecessary. Presently research is ongoing to better understand the role of the phenomena of "dambreak" floods which have been observed in Northwest streams (Benda and Zhang, 1989, Johnson, 1991). When we better understand the role of debris dams and subsequent "dambreak" floods, it may be possible to include them more completelyin the classification scheme. This example illustrates that the classification is not "set in stone" but has been designed to evolve over time as a better understanding is obtained of such physical processes.

FIELD RECONNAISSANCE & PROFESSIONAL REVIEW

The second phase of this project involved an evaluation of the proposed classification scheme for the State of Washington. This was accomplished partially through a ten day itinerary of visits to streams in various physiographic regions of the state, often in the company of local experts (see Appendix B for a list of local experts). At other times where local expertise was unavailable relative to our field schedule, we examined and classified streams that had been previously included in the Ambient Monitoring Project for TFW. Most of the streams investigated were categorized in that study as Type 3 streams. We sent earlier drafts of this document to various researchers in the fields of forest practices, upland channels, and hillslope stability (Appendix A). In this section of the report we will summarize our findings from the field evaluation, and present and comment upon reviews of this scheme from those local experts along on the field reconnaissance, and from mail and phone reviews. Actual site descriptions and analysis are presented in Appendix B.

Discussion of Field Reconnaissance & Professional Review

In most respects the field reconnaissance and discussion with local experts added to our confidence that the classification scheme was scientifically robust and practically useful. Visits to the various parts of the state having diverse climates, rocks, soils, history of landuse, and vegetation made it clear that a single scheme could be applied across the state.

The field work did suggest that some changes be made in setting some of the boundaries. The primary changes were made in terms describing the channel's propensity to transport/deposit debris flows and these changes were made because of additional information and literature of which we were made aware. The criteria for stable and unstable hillslopes was modified in order to be conservative; the critical ordinate value on Figure 11 was lowered from 1.0 to 0.80. This shift is not constrained by data but rather aims to incorporate other effects/issues including the role of hillslope convergence upon pore pressures, the potential for local slopes to be steeper than the characteristic slope value used in calculations, and the history of landuse or future landuse as it might affect stability.

Otherwise we found the incorporation of a factor of safety into the first panel of Figure 11 very useful. This permitted differentiation of slopes with equal gradients in the Cascades from those in the Northeast (Colville) in terms of the likelihood of failure. The unlikelihood of debris flows on Northeastern slopes fell out of the analysis of characteristic degrees of saturation in the factor of safety calculation. This conforms with observation. On the other hand, the likelihood of debris flows in the Cascade slopes from the analysis corresponds with observation. The factor of safety analysis also allows treatment of bedrock-bound valley slopes which do not in the short term contribute debris flows, but by their steepness are likely to be classified in other schemes as unstable. Field visits and our reconnaissance helped convince us that one can differentiate between stream response to debris flow. Following Benda and Cundy (1990) among others, we incorporated in the scheme domains in which in-channel debris flows from upstream tend to erode or deposit channel sediments.

Several phenomena described in parts of the Pacific Northwest as occurring in steep forested drainage basins, such as moving organic debris, are not treated in the classification. While we saw some evidence for such events and the influence they can have upon the channel, we feel that at this point there is not sufficient information about these phenomena for them to be incorporated into the scheme. Perhaps at a later time, as more is learned empirically and theoretically, domains where such events are likely can be delineated within the present scheme.

Finally, the role of organic material, particularly large logs, root wads, and slash was re-evaluated during the site visits. Clearly this material is very important in the role of governing roughness, storage of sediment, and providing alluvial architecture. However, we have no better insight in how to bring these elements into the classification scheme.

In summary, our preliminary evaluation of the classification scheme in various parts of the State, suggests it should be a useful tool for identifying and qualitatively estimating how sensitive streams and stream reaches are to environmental degradation. Nevertheless, before sensitive streams and stream reaches are to environmental degradation. Nevertheless, before general application of this classification scheme we would argue for a more detailed study and field verification of it's usefulness.

LINKAGE TO WATER QUALITY & FISHERIES IMPACTS

The classification is not merely an end unto itself. Its purpose is to identify streams and valleys likely to respond in a similar manner and to warrant similar regulations to prevent or at least to minimize environmental degradation. While it is beyond the scope of this report to provide a complete documentation, suggestions and examples of the potential use of the classification are made.

Mass wasting processes are of most concern for moving large amounts of material rapidly into stream channels. In an AD5 setting where slopes are steep enough and the valley narrow enough for the debris flow to enter the channel, the effects of such a failure are likely to be dramatic downstream because the channel can carry much of the material in suspension. In such an energetic setting, the downstream effects on water quality, gravel quality for fish habitat and spawning, and esthetics may be seriously affected. On the other hand if the valley geometry was identical, but the channel was of class 1 (as defined from Figure 11, plate 3), large bed material sizes with low suspended load, downstream effects would be drastically reduced. Even if the channel type were still a 5, but with a wider valley, the likelihood that a debris flow would have entered the channel is reduced and the possibility of storage of the material on the floodplain within a short distance is greater. In such a setting, the concern about downstream effects of the same potential hillslope failure are reduced. The classification should be viewed as a tool to guide levels of effort to minimize off-site sediment and water quality problems. A summary of potential local impacts and downstream impacts are presented in Tables 3 and 4. We are specifically considering turbidity and fine sediments and their negative impacts on fisheries and water quality.

DELINEATION BETWEEN TYPE 3 AND 4 WATERS

As previously discussed, the present stream typing system used in the State of Washington is based on a number of factors including size, consumptive use, and the presence of anadromous or resident fisheries. The different ways that one types a stream cause an obvious problem in maintaining consistency in actual field differentiation of Type 3 and 4 streams. Different people have differing levels of experience and look at different variables in their efforts at channel typing. The main objective of this study was to develop a process-based stream classification for small streams. A subsidiary goal was to attempt to delineate, using a process based approach between Type 3 and 4 waters, as they are presently called, and/or to link the present system to the process-based classification.

We were unable to define such a geomorphic process breakpoint from either phase of this investigation, except in the sense that streams with high potential for debris flows impacting the channels can be identified using the classification scheme. We feel that the small stream classification is applicable for small streams including Type 3, 4 and 5 waters. Using Figure 11, and Tables 3 and 4, it is possible to understand processes effecting water resources, and to assess relative environmental sensitivity of each stream class. Accordingly, forest practices and their impacts can be more adequately evaluated using such information than from use of the present system.

CONCLUSIONS AND RECOMMENDATIONS

A small stream classification based on geomorphic, physically-based processes has been developed for use in Washington State. That classification is presented in three figures; initially relating valley side slope gradient (soil properties) to channel gradient, then valley width and channel width, and finally relating the depth-slope product and bed sediment grain size. This classification scheme has been developed independent of regional variability within the State. Regional variability exists but can be addressed within a single stream classification scheme. Field assessment of the classification confirmed our original confidence in the validity of the methodology, though some slight modifications were made in the final scheme. This classification was developed after a thorough literature review of classification schemes was conducted in conjunction with identification of important physical processes in Washington's drainage basins. Instream and downstream water quality and fisheries have also been evaluated for the various stream classes. For example, effects of forest practices on fisheries and water quality are usually much greater in suspended load than bedload streams, as a result of the transport of finer sediments downstream to spawning areas as well as increased turbidity and suspended sediment concentrations. The classification can also deal with a stream in which larger sediment sizes are of concern. For example, transport of gravels and cobbles can fill pools in pool-riffle sequences. Additionally, deposition of large volumes of larger clasts can cause local bank erosion and modify channel geometry. Prior to general regulatory application of this classification scheme, a detailed field testing of its accuracy and effectiveness is recommended.

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APPENDIX A - LIST OF RESEARCHERS REVIEWING DOCUMENT

Lee Benda, University of Washington
Matt Brunengo, Washington State Dept. of Natural Resources
Paul Kennard, Tulalip Tribe
Tom Koler, U.S. Forest Service
Glen MacDonald, Washington State Dept. of Ecology, USDA Forest Service
Dave Montgomery, University of Washington
Kate Sullivan, Weyerhauser

APPENDIX B - FIELD RECONNAISSANCE

A field site reconnaissance was conducted during the first two weeks of August 1991 to evaluate the validity of the small stream classification method. Field sites were visited throughout the state and are located by number on the map in Figure 12. The stream name and measured parameters are listed in Table 5. Stream and geomorphic parameters were measured at approximately half of the sites, while the other sites were only visually inspected. Half the sites were selected in consultation with experts and TFW cooperators working in various areas of the state. Those sites were visited with some of those same individuals. Additional sites were selected from locations used in the TFW Temperature Study. Additional streams were identified and visually assessed as we progressed across the state. A number of small streams were observed that are not documented in this appendix as they were conducted in more of a windshield survey. The main purpose of the field evaluation was to obtain an overall understanding of sedimentation processes and their variance throughout the State.

It should be noted that the field assessment is not a detailed inventory of stream channels throughout the state, nor is it a systematic statistical one. It was impossible to conduct such an analysis under the project budget. Correspondingly, it was our goal from the beginning to conduct a field reconnaissance that allowed us to discuss various basin and channel processes with researchers and cooperators familiar with differing regional and basinwide characteristics, as well as to conduct some detailed measurements of stream channels. It is anticipated that as the classification system comes to be used throughout the state that a more detailed systematic evaluation can be made. As an outgrowth of more detailed evaluation, information may become available which will allow modification of some of the more arbitrary boundaries of Figure 11. It is our present feeling that the small stream classification is generally applicable to small streams throughout Washington. A more detailed description and photographic inventory of the sites follows.

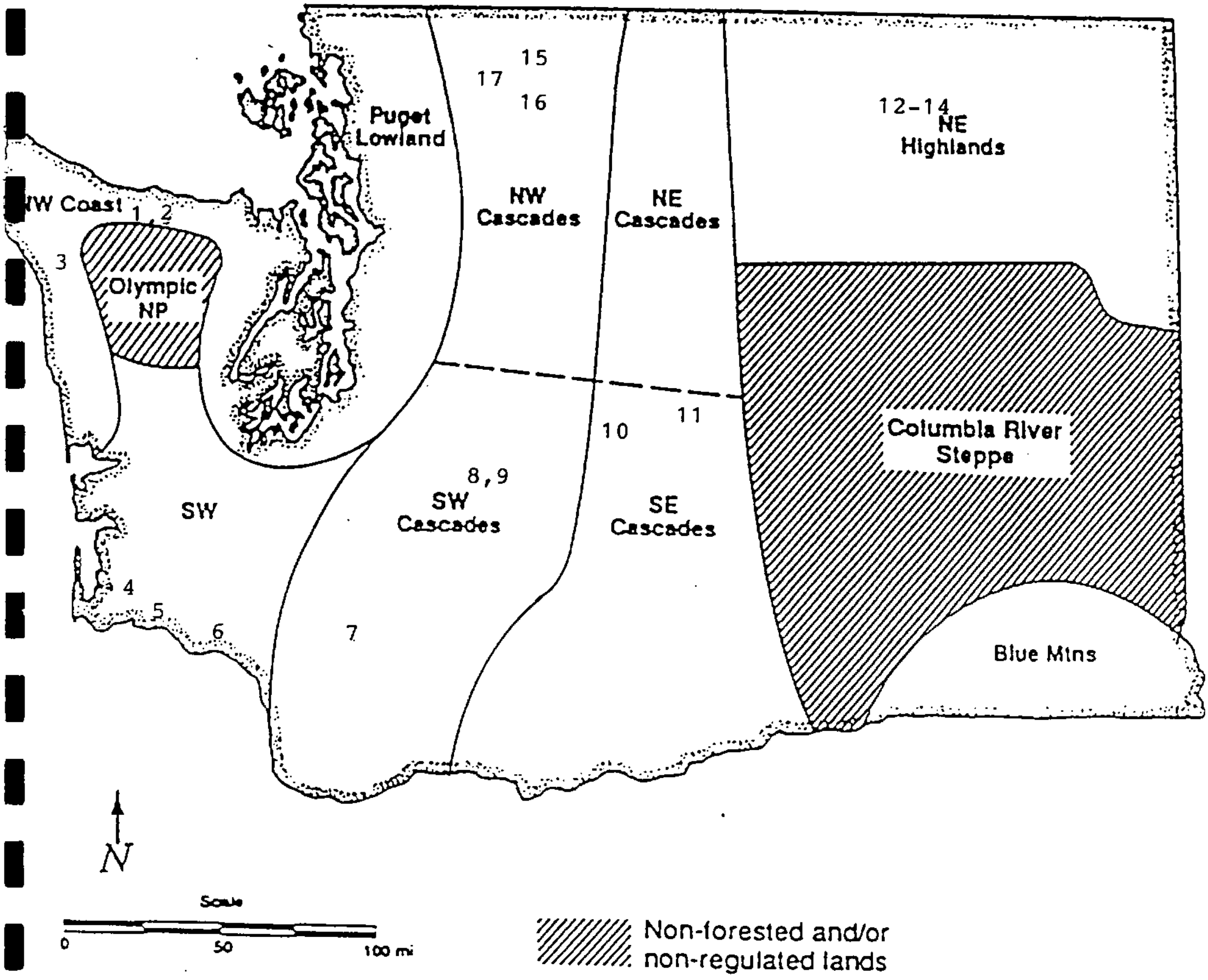

Figure 12. Field Reconnaissance Map.

Table 5. Field Site Classification.

TABLE 5. FIELD SITES

STREAM	TRIBUTARY TO	REGION	SLIDESLOPE GRADIENT	CHANNEL GRADIENT	VALLEY WIDTH M	CHANNEL WIDTH M	CHANNEL DEPTH M	GRAIN SIZE (cm)	STREAM CLASS
1. Pistol Cr. & Tribs.	Soleduck River	NW Coast Olympic Penninsula	N.A[1]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2. Spruce Creek	Pistol Creek	Olympic Penninsula	0.60	0.100	10	2.0	0.4	4.0	AD3
3. Hoh R. & Tribs.	Pacific Ocean	Olympic Penninsula	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
4. Sweigeler Creek	Naselle River	Southwest	0.25	0.040	35	7.0	0.7	4.0	NF2
5. Trib to Grays R.	Grays River	Southwest	0.10	0.002	30	9.0	0.8	2.5	NF2
6. Germany Creek	Columbia River	Southwest	0.60	0.018	20	12.0	1.0	18.0	AD/MD1
7. Trib to S. Fk. Toutle	S. Fk. Toutle	SW Cascades	0.80	0.040	40	9.0	0.9	11.0	OD1
8. Kiona Cr. & Tribs.	Cowlitz River	SW Cascades	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
9. Mineral Cr. & Tribs.	N.Fk. Nisqually River	SW Cascades	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
10. Cold Creek	Yakima River	SE Cascades	0.10	0.025	50	6.0	1.0	30.0	NF2
11. Blue Creek	Swauk Creek Yakima Trib.	SE Cascades	0.10	0.03	60	3.0	0.4	6.0	NF3
12. Narcisse Cr.	Colville River	NE Highlands	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
13. Ten Mile Cr.	Narcisse Creek	NE Highlands	N.A	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
14. Palmer Creek	Narcisse Creek	NE Highlands	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
15. Sibley Creek	Cascade River	NW Cascades	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
16. Higgins Cr.	Deer Creek	NW Cascades	0.15	.0087	10	2.5	6.6	15.0	NF1
17. Unamed Cr.	Skagit River	NW Cascades	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

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[1] Detailed measurements were not taken at the site.

Pistol Creek and Tributaries

Pistol Creek is located on the north side of the Olympic Mountain Range. We visually investigated a number of streams in the company of Matt O'Connor, a University of Washington researcher investigating the effects of woody debris on channel morphology. The stream system is dendritic in nature with some glacial cirque lakes. Significant clearcuts have taken place. Additionally, a fairly large portion of the basin has been the site of heavy fire damage in the recent past. Mr. O'Connor has two study sites in this drainage system. The Spruce Creek site was classified as a AD3 channel.

Panorama of Pistol Creek Drainage

View Downstream at Spruce Creek, One of Matt O'Connor's Field Sites

Hoh River and Tributaries

Another full day was spent in the field with Matt O'Connor obtaining an overview of the Hoh River Valley and it's tributaries. The Hoh River flows west from the Olympic Mountains and empties into the Pacific Ocean near the town of Forks. The south side of the Hoh River Valley has numerous debris flows some of which were triggered by side casting. More clearcuts are evident on the south side of the valley. The north side tributaries have debris flow evidence but they are more confined to stream channels and do not appear to be as destructive as those to the south.

South Side Hoh River Tributary Debris Flow

South Side Hoh River Valley Debris Jam-Large Sediment Deposit Upstream

North Side Hoh River Valley Tributary, View Upstream

North Side Hoh River Valley Tributary, View Upstream

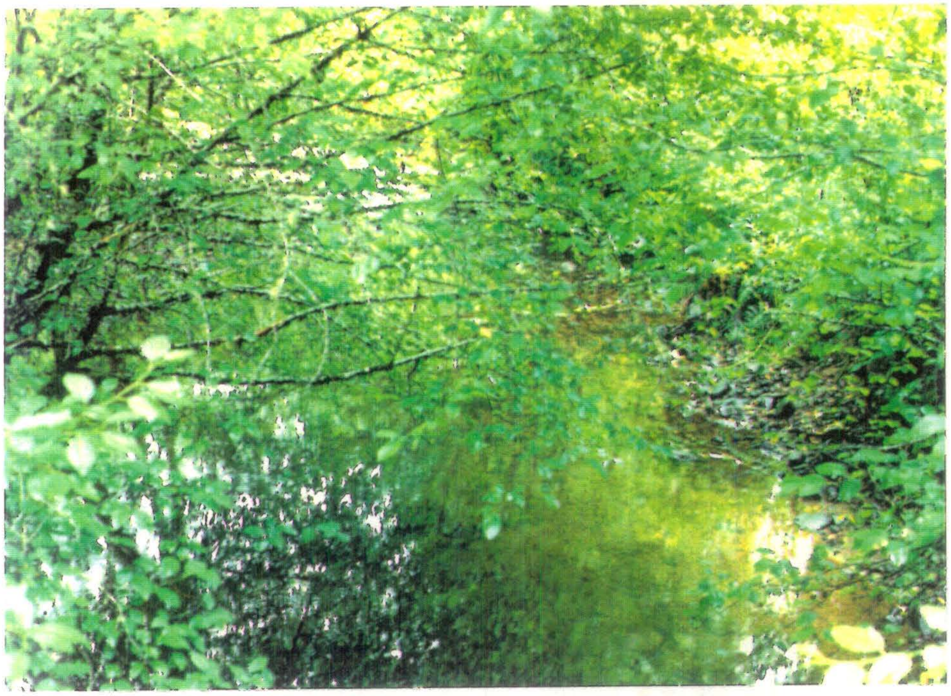
Sweigeler Creek

Sweigeler Creek is a tributary to the Naselle River which drains into Willapa Bay along the southwestern Washington coast. It was a site used in the Timber/Fish/Wildlife Temperature Study and was designated by that study as site BC. Site morphologic parameters are presented in Table 5. The stream was classed by the Temperature Study as Type 3. The stream was typed as an NF2 stream using the new classification scheme.

View Downstream of Sweigeler Creek

Grays River Tributary

An unnamed Grays River tributary was investigated using the new methodology. This site was located in the Southwest Region of Washington and is part of the Columbia River system. The site was classified as an NF2 stream.



Unnamed Grays River Tributary, View Downstream

Germany Creek

The Germany Creek site was one previously identified by the TFW Temperature Study as a Type 3 stream. Site designation from that study was BB. Germany Creek is tributary to the Columbia River. Morphologic parameters are presented in Table 5, and the stream was classed as either AD1 or MD1 using the new classification scheme.

View Upstream Germany Creek

South Fork Toutle River Tributary

An unnamed tributary on the south side of the South Fork Toutle River Valley was classified as a OD1 stream. The geomorphic parameters are listed in Table 5.

View Upstream South Fork Toutle River Tributary

Kiona Creek, Mineral Creek and Tributaries

One day was spent investigating the Kiona Creek and Mineral Creek watersheds in the company of Mr. Matt Brunenga of the Washington State Department of Natural Resources. Mr. Brunenga has been studying landslides within these basins for some time. Both streams are located in the Southwest Cascade Region and are separated to the north and the south by a mountain range. Kiona Creek is on the south side and Mineral Creek to the north, with Mineral Creek being tributary to the Nisqually River. Kiona Creek has been subject to extensive landslides and debris flows in the last few years. The Mineral Creek watershed has flatter gradients and wider valleys.

Lower Kiona Creek Debris Flow Deposits, View Upstream

Small Tributary Drainage near Kiona Creek Headwaters

Kiona Creek Tributary

Kiona Creek Tributary Debris Flow, View Downstream

Debris Flow, Kiona Creek Tributary

View Upslope at Kiona Creek Landslide Source Areas

Mineral Creek-Slope Failure due to Upstream Culvert Overtopping

Gentle Gradient Reach Mineral Creek, Ponds due to Flat Slope and Beaver Ponds

Yakima River Tributaries - Cold Creek and Blue Creek

Cold Creek is a Yakima River tributary which drains into Keechelus Lake. It was classified using the new technique as an NF1 stream. Blue Creek, tributary to Swauk Creek and the Yakima River, was classified as NF3.

Above-View Downstream Cold Creek. Below-View Downstream Blue Creek

View Upstream Blue Creek

Narcisse Creek and Tributaries

Several streams, including Narcisse Creek and its' tributaries, Ten Mile Creek, and Palmer Creek were investigated near the Colville area. We were accompanied on this inspection by Mr. Bob Anderson, of the Washington State Department of Natural Resources. Generally speaking, hydrologic conditions are drier in this part of the State, vegetal cover is less dense, slopes are not as steep, and logging practices differ from the west side of the State. Clearcuts are used significantly less often in logging operations in this part of the state. As a result, the most appropriate use of the classification scheme should include actual computation of the Factor of Safety (Terzaghi and Peck, 1967) for use in slope stability analysis, rather than use of the sideslope gradient. This can be done using general values for various soil types and geology, and degree of saturation, or using actual soil sample measurements.

Narcisse Creek

Small Drainage Upslope in Narcisse Creek Watershed

Panorama of Clearcut near Colville

Typical Logging Operation in this Area

Cascade River Tributaries

Several tributaries to the Cascade River were investigated in the Northwest Cascade Region. Geomorphic processes in these systems is driven by landslides and debris flows.

Sibley Creek, View Upstream

View Upstream North Fork Cascade River

Higgins Creek

Higgins Creek, originating on Mt. Higgins and tributary to Deer Creek, was one of the TFW Temperature Study sites, and was designated as Site HD in that study. It was typed as a Type 3 water. Measured morphologic variables are listed in Table 5. Higgins Creek was classed as an NF1 stream using the new system.

Higgins Creek, View Upstream

Unnamed Skagit River Tributaries

Several small Skagit River tributaries were the last systems investigated in the field reconnaissance. These were conducted in the company of Mr. Tim Beechie of the Skagit System Cooperative. The streams had several upslope landslides and significant downstream debris flows as the result of the 1990 storm season. Those debris flows had significant runout distances which impacted downstream culverts and roads.

Debris Flow Deposits, View Upstream