# Fluvial Geomorphology Appendix

*Geomorphology* means, literally, the study of the form or shape of the earth. More specifically, it is the science of the shape of the earth's surface, the processes that mold this surface, and consequently, how the surface will change its shape or evolve over time. *Fluvial geomorphology* is the study of landform evolution related to stream systems. As an integrative field it includes the related disciplines of geology, hydrology and hydraulics, sediment transport, soil mechanics, and the mechanical effects of vegetation. Any project that potentially affects natural stream processes requires a basic understanding of the fluvial geomorphology of the system in question.

## 1 Basic Concepts in Fluvial Geomorphology

### *1.1 Spatial and Temporal Scale*

Stream channels are dynamic systems and are constantly changing both spatially and temporally. When evaluating a stream channel, it is important to consider both the spatial and temporal scale at which an evaluation or investigation is conducted, as well as the scale of the inputs and processes affecting the stream channel. There is a hierarchy of variables affecting stream systems. The foundation of this hierarchy is the triad of climate, geology, and topography[1]. This triad of variables determines the independent variables affecting stream channels – hydrology, sediment supply, and vegetation, which vary about fairly-constant averages in a temporal scale, but can change dramatically on a spatial scale within a watershed.

The variables that define channel process and form typically change downstream through a watershed, resulting in predictable spatial variability in habitat form and function. The downstream change in hydrologic regime through a watershed can be generally described as an increase in volume accompanied by a decrease in flow variability. Sediment transported can be generally described as increasing in volume downstream, but decreasing in particle size. Local variations in geology and bank material, as well as depositional patterns, may result in highly variable sediment character on a reach scale.

On a temporal scale, stream channel form and process are affected by climate change or cyclical fluctuation (such as drought), seasonal weather variations, and natural and anthropogenic disturbances to the channel and watershed. Climate change typically occurs over decades, though cycles of climate patterns may occur on a scale of years. Over short time scales (one to 10 years), some disturbances caused by human activities can be assessed. For example, overgrazing can affect hydrology and sediment load, potentially causing channel erosion and incision and resultant habitat degradation. Defining the temporal scale of observation, therefore, is essential for assessing relationships among various attributes of fluvial systems.

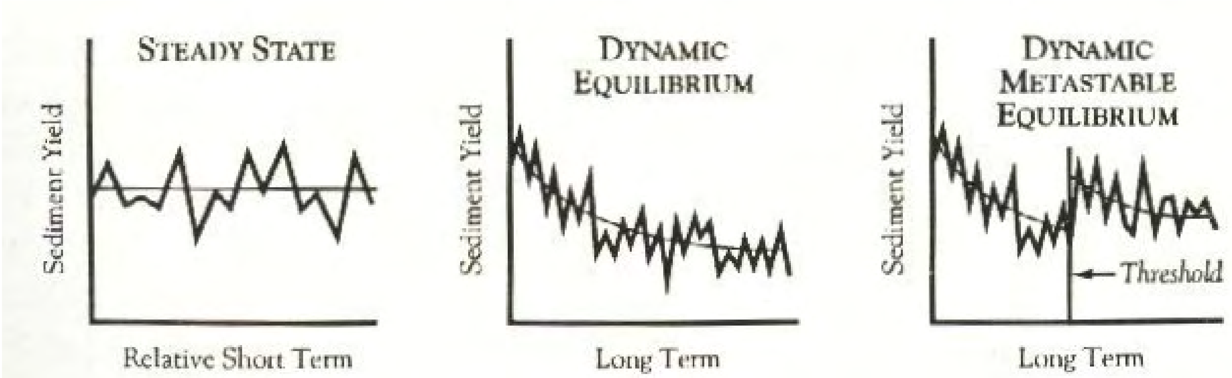
### *1.2 Equilibrium*

One of the fundamental aspects of understanding stream channel behavior is that stream channels tend toward an equilibrium state in which the input and output of mass and energy to and from a specific reach are equal.[2] *The destabilization of streams typically occurs when the balance* *between sediment input and sediment output from a reach becomes altered.* A corollary to this is that overall channel morphology (sinuosity, channel width, and slope) remains relatively constant throughout the transfer of mass and energy, assuming inputs to the channel are relatively constant. The term equilibrium in the context of stream channels refers to the relative stability (defined below) of the channel system and its ability to maintain its morphological characteristics over some period of time and range of flow conditions, accommodating minor variations in inputs. In reality, perfect equilibrium does not exist in natural streams. However, natural streams do tend to develop channel sizes and shapes that accommodate and reflect the typical hydrologic regime and the character and quantity of sediment supplied by the watershed. These streams are said to be in a state of approximate equilibrium.[3]

Numerous authors[2 3 4 5] have presented discussions on and defined variations of the concept of equilibrium. Definition of the various forms of equilibrium is dependent upon the time scale under which equilibrium is scrutinized, and the same channel process may be defined as differing forms of equilibrium, or even as non-equilibrium, simply by virtue of differing periods of observation. Due to the complexity and variety of definitions of varying forms of equilibrium, these variations are not defined here. For further discussion of equilibrium, refer to Graf (1988)[2], and Thorn and Welford (1994)[6].

Stream channels commonly exhibit many forms of equilibrium, and are subject to changes in equilibrium resulting from anthropogenic influences, catastrophic events, and gradual changes in climate. For example, short-term fluctuations in a given variable, such as channel depth, may occur throughout a stream reach, but the longer-term, constant mean value of the variable is maintained. An example of this occurs when channels adjust to scour and fill associated with seasonal flooding. It is important to note that the time scale of observations is critical for defining an equilibrium state – if the time scale is too short, the mean value of the variable in flux will not be accurately determined. Following a low probability flood (e.g. a 50-year flood), a given reach of channel may exhibit bed incision and bank erosion. However, in subsequent years, the bed and banks may recover to previous channel dimensions. If observed only over a single year following a flood, the channel will not appear to be exhibiting equilibrium conditions. If observed over a decade following the same flood, the channel would otherwise exhibit equilibrium conditions.

Similarly, a stream may adjust its character gradually in response to gradual environmental change, such as a slow change in base level (the level below which a stream cannot erode, such as a lake at the channel mouth or a bedrock sill). In this instance, the stream undergoes a complex pattern of erosion, deposition, changes in sediment load and renewed incision as it adjusts to the new base level. The time scale through which equilibrium is exhibited may span hundreds or thousands of years. At any given point in time during the adjustment, the channel may exhibit equilibrium conditions; though over time the equilibrium changes. This is referred to as *dynamic equilibrium* (see **Geomorphology Figure 1**).




**Geomorphology Figure 1**: Concept of dynamic equilibrium expressed as a function of sediment yield – the total sediment derived from a watershed per year. From *California Rivers and Streams*, J.F. Mount[7]. Copyright permission is being sought.

Human influences on channels and their inputs can affect rapid destabilization of equilibrium conditions, or force rapid change of equilibrium values. Human influences are varied and complex and can affect all variables influencing channel equilibrium, channel processes and habitat. The most common and drastic human influences are related to urbanization, and include changes to the hydrologic regime and imposing constraints on the channel, such as levees, revetments or culverts. Removal of large wood from the channel is also common, and can have significant impacts on channel processes and habitat.

Most 'healthy' stream systems with high quality habitat and other attributes that we value are distinguished by complex energy dissipation mechanisms that include primarily channel roughness elements (e.g. large wood, boulders, complex channel planform and bedform). Equilibrium in such channels is maintained in part by the existence of these energy dissipation mechanisms that reduce the channel's capacity to erode and transport sediment. In-channel roughness creates complex hydraulics and reduces flow energy. Floodplains play an equally important role during overbank events by increasing resistance to flow, rather than concentrating energy within the channel. Vegetation is particularly important to dissipating energy at channel bank margins and in floodplains. Vegetation provides critical stabilizing and roughening functions that make possible the existence of channels with high aquatic habitat value, that is, those with high hydraulic and structural complexity. Collectively, the energy-dissipating functions of in-channel wood, structural complexity, floodplains and vegetation are largely what maintain the system's ability to balance the inputs and outputs of water, sediment, and kinetic energy.

Habitat form and function is also significantly influenced by and dependent upon disturbance to the channel system. White and Pickett[8] define disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". The superposition of short-term variability in inputs (such as seasonal variations in hydrology) and longer-term disturbance regimes (e.g. patterns of major disturbances, such as landslides and fire), which are characterized by even greater variability in magnitude and timing of inputs, results in unique suites of geomorphic processes that dictate physical habitat structure, dynamics and evolution. Following a disturbance, the system undergoes a period of recovery to pre-disturbance equilibrium conditions. The rate of recovery is generally more rapid at first, slowing asymptotically as equilibrium is approached. Disturbance is most important to geomorphic form and process when this recovery time is greater than the time between significant disturbances.

### *1.2.1 Regime Theory and Channel Geometry*

Prior to extensive use of equilibrium principles by geomorphologists, hydraulics engineers used the concepts of equilibrium in *regime theory*[2]. Regime theory is based on the tendency of a stream system to obtain an equilibrium state under constant environmental conditions (i.e. constant water discharge, as in a canal). It consists of a set of empirical equations relating channel shape to discharge, sediment load and bank resistance. The theory proposes that dominant channel characteristics remain stable for a period of years and that any change in the hydrologic or sediment regime leads to a quantifiable channel response (such as erosion or deposition). Stream reaches that are "in regime" (meaning "in equilibrium"[9]) are able to move their sediment load through the system without net erosion or deposition and do not change their average shape and dimensions over a short time period.[10]

Since real streams do not exist under constant conditions, regime theory is, by definition, not strictly applicable to them. However, even though the water discharge, and thus the sediment transport, in a real stream varies continuously over time, it can be shown that there exists a narrow range of discharges that, averaged over the long term, moves most of the sediment load. This *effective discharge* can in principle be said to mimic the *dominant* or *channel-forming discharge* used in the regime equations. As will be discussed later, more current research has focused on the *bankfull discharge,* and has attempted to implicitly equate bankfull with the dominant discharge used in the regime concept and the effective discharge that moves most of the sediment load. Thus, the older regime equations have been supplanted by equations that define the dimensions of the channel in terms of bankfull flow (to be defined later). In theory, then, there exists a *bankfull hydraulic geometry,* a predictable pattern, profile and shape of an alluvial channel determined by bankfull flow. It should be noted that hydraulic geometry is only expected to be well defined in quasi-equilibrium *alluvial channels*, that is, channels that are built by the moving water, and is not applicable to streams located in landscape positions where either erosion or continual deposition is the dominant process, such as alluvial fans, deltas, headwater source areas or confined reaches that inherit their geometry from the valley sides.

Regime theory and its successor, bankfull hydraulic geometry, has formed the basis for a large body of work in fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes.[11] According to R. D. Hey[10], there are nine measurable variables used to define equilibrium channel geometry. These characteristics are considered dependent variables for stream reaches in regime:

1. Average bankfull channel width (w),
2. Average bankfull depth (d),
3. Maximum depth ($d_m$),
4. Average bankfull velocity (V),
5. Height ($\Delta$) of bedforms,

6. Wavelength ($\lambda$) of bedforms,
7. Channel slope (S),
8. Meander arc length (z), and
9. Sinuosity (*P*).

The six independent variables that control changes in channel dimension and shape are:

1. Discharge (Q),
2. Sediment load ($Q_s$),
3. Size of bed material (D),
4. Bank material and character,
5. Bank and floodplain vegetation (riparian and/or upland species), and
6. Valley slope ($S_v$).

Changes in any of these controlling variables may result in a new channel geometry that represents a stable morphology in a new equilibrium state.

### *1.2.2 The Bankfull Concept*

It has been said that "rivers construct their own edifice." That is, the shape of the channel (planform, cross-sectional shape, and profile) is sculpted by the river as it erodes and deposits sediment according to the laws of physics. The end result is a quasi-equilibrium channel, having just the right morphology to move the sediment and water carried by the river. One consistent characteristic of a self-formed alluvial channel is the presence of a floodplain. A *floodplain* is a relatively flat, depositional surface adjacent to the channel, formed by the river under its present climate and sediment load, and overflowed during moderate peak flow events[12].

This definition contains several key points. First, the floodplain is a *depositional* surface, formed by the river, not an erosional surface or a surface formed by other non-fluvial processes that can deposit sediments. Secondly, the floodplain is formed under the current climate and sediment load. Flat surfaces may be present from previous eras of differing climate and/or sediment load, and these surfaces are called *terraces*. Terraces are generally not "geomorphically active," that is, they are not currently being built by river depositional processes. Finally, the floodplain is overflowed, on the average, several times per year, during moderate peak flow events (such as a 1.5-year or 2-year flood). Terraces may be overtopped, but only by larger, less frequent floods (e.g. 50-year or 100-year events). The inner edge of the floodplain, or the point of incipient flooding, is called *bankfull*. The bankfull channel refers to the channel cross-section below the elevation of the floodplain.

In theory, the bankfull channel is sized to convey the effective discharge. That is, over the long term, most of the sediment load moves at flows bracketing bankfull. Smaller discharges occur much more frequently, but carry little or no sediment due to lack of sufficient shear stress, thus contributing little to the overall sediment budget. Large discharges have the shear stress to move very high sediment loads, but occur rarely, again contributing little to the yearly sediment budget. Thus, it is the moderate flows, centered about bankfull, which move most of the sediment over the long term, and the channel forms itself into a shape to most efficiently convey these flows. The bankfull channel tends to be stable at higher flows as well, since these flows dissipate their potentially high shear stress by spreading out over the floodplain. Overbank flow creates a wide, shallow cross-section, reducing velocities and shear stress to the point where sediment carried in suspension is deposited there, contributing to floodplain construction.

It should be noted here that bankfull is a geomorphic concept. Although bankfull may, on the average, correspond to a certain statistically-derived flood (commonly asserted to be the 1.5-year flood), bankfull is defined by the floodplain geomorphic surface, in the field. If this surface is not present, then bankfull is not defined. Often, secondary indicators such as scour or moss lines on rock surfaces, types or presence of vegetation, changes in substrate texture, etc. are used to delineate bankfull in the absence of a floodplain. Such indicators are only valid if they have been "calibrated" by correlation with a floodplain or incipient floodplain nearby.

## *1.3 Channel Pattern*

Researchers have variously classified channel patterns as straight, braided, meandering, or anastomosing based on the number of intersecting channel threads and the degree to which the channel meanders[3 13 14]. Straight channels are rare in nature, as the channel thalweg (deepest portion of channel) typically wanders from bank to bank even within a straight channel. Straight channels usually exist only in steep narrow valleys where geologic control prevents meandering and are dominated by sediment transport and colluvial processes. They tend to accumulate or store little alluvial sediment, and the banks and bed are usually dominated by colluvial material that enters the channel via erosion and mass wasting. Meandering channels, by contrast, wander back and forth across a valley and are typically alluvial. Both straight and meandering channels consist of a single thread channel. Braided channels differ in that they exhibit numerous channel threads separated by islands or bars, which are often submerged at high flow. Braided channels are dominated by sediment deposition processes and are alluvial. Multiple thread channels that are relatively narrow and deep, and are separated by well-vegetated, stable islands, are referred to as anastomosing. Many of the larger rivers in Western Washington were originally anastomosing channels, with large wood playing a dominant role in controlling channel and bar position, stability, and dynamics[15].

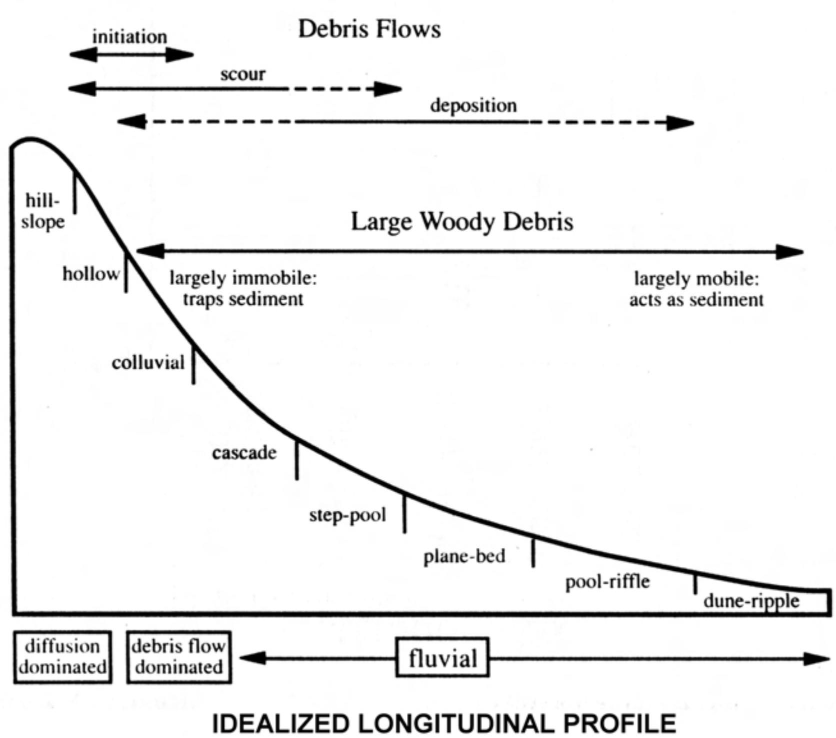
Channel pattern can be largely explained in most rivers by the interaction of channel slope, bankfull discharge, bed and bank material, vegetation, and available sediment load[16]. Channel patterns can exhibit similar forms in either equilibrium condition or in a condition of disequilibrium. For example, a braided channel may be considered in equilibrium condition across an alluvial fan, but may indicate a degraded condition in a lower gradient alluvial valley. As such, channel pattern can be a key indicator of severely degraded systems where factors leading to their degradation typically occur on a watershed scale. Differentiating between similar channel patterns in equilibrium condition or in degraded condition is best determined through reviewing historic channel condition with respect to changes imposed on the channel and its watershed.

## *1.4 Channel Classification*

In the late twentieth century, several more-sophisticated schemes for describing river channels were developed. Some, such as the Channel Evolution Model (CEM)[17] discussed below, are highly useful but limited in scope to certain geomorphic settings. Others, such as those of Nansen and Croke[18], Whiting[19], and Brice[20] are potentially useful but have not gained widespread acceptance in this country. In the Pacific Northwest, the systems of Montgomery and Buffington[21] and that of Rosgen[22] are by far the most popular.

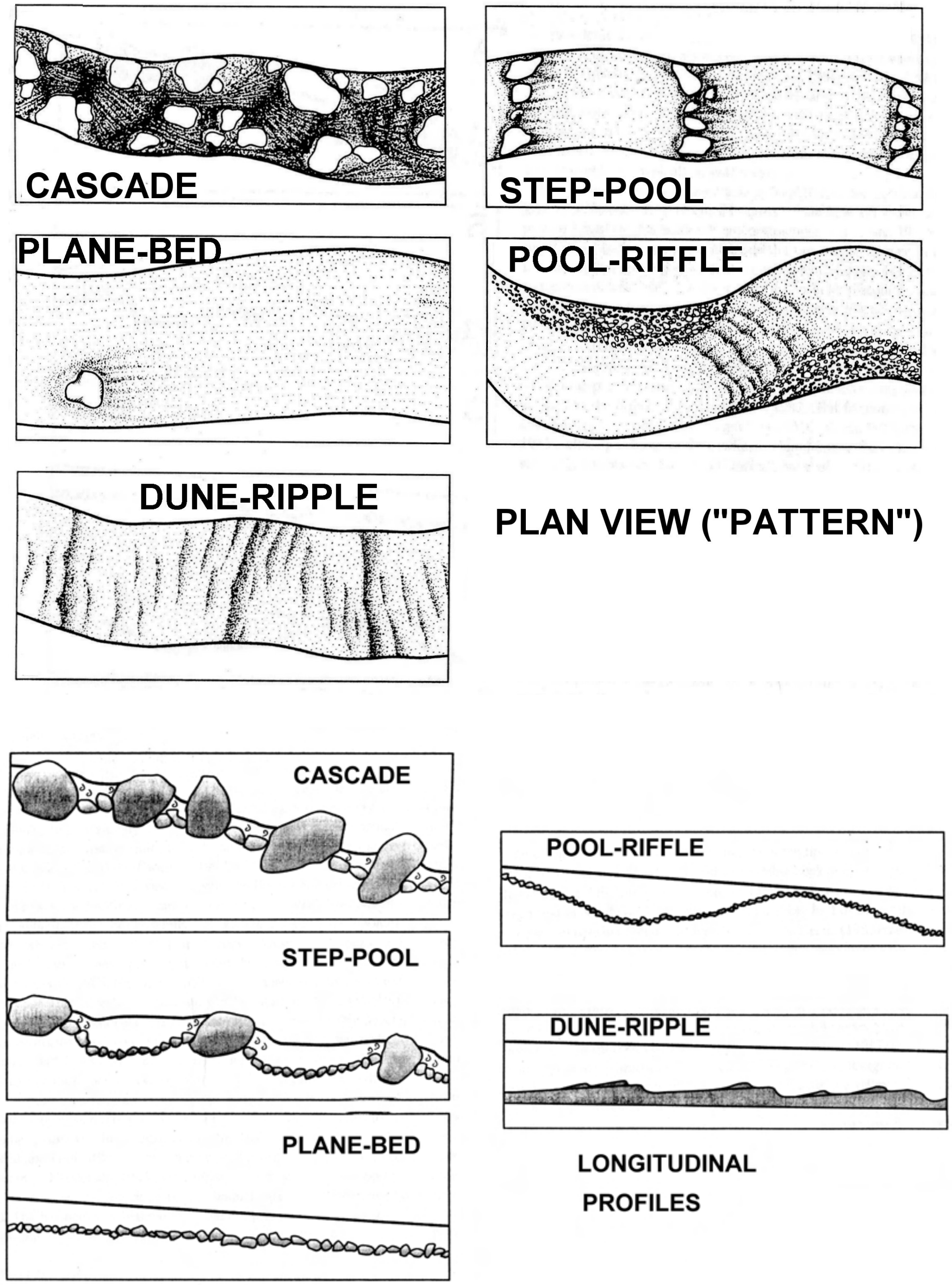
Montgomery and Buffington's classification (see **Geomorphology Figure 2**) is based on a hierarchy of spatial scales that reflect different geomorphic processes and controls on channel morphology. A conceptual, large-scale longitudinal view of the river channel from headwaters to lowlands is presented, in which a predictable sequence of channel morphologies is linked to changes in dominant sediment sources and transport processes. Progressing from top to bottom in the stream network, one encounters hollows, colluvial channels, cascades, step-pool, plane-bed, pool-riffle, and dune-ripple morphologies. In this progression from top to bottom, sediment sources shift from hillslope surface erosion and mass wasting to hydraulic erosion of colluvial material to erosion of alluvial material and influx from upstream of fluvial sediment. Mass wasting (debris flow) processes shift from initiation to sour to deposition. Large wood shifts from being largely immobile and trapping sediment to being mobile and acting as sediment. Slope decreases. Sediment size decreases from large clasts seldom moved by hydraulic forces, to cobble, then gravel, then sand-bed systems, in which bed forms (dunes, ripples, etc.) rather than individual grains characterize sediment movement. The seven basic channel morphologies are arrayed in a way that reflects this continuum of process (see **Geomorphology Figure 3**). These channel types are defined by qualitative morphological descriptions and sketches rather than physical measurements. An eighth channel type, the bedrock channel, is also included, but is more irregular in its spatial occurrence.

More broadly, Montgomery and Buffington see the river landscape as a continuum from "source reaches" to "transport reaches," and then to "response reaches." Source reaches are headwater areas where long-term average erosion rates (tonnes/ha/year) are high, and consequently, sediment in transport tends to be locally derived rather than routed in from upstream. In source reaches, steep channel slopes and proximity to catastrophic events such debris flows do not allow much fluvial sediment to accumulate in the channel. Transport reaches, like source reaches, function to efficiently route sediment delivered from upstream, and experience flow energy that precludes extensive alluvial deposit formation. But in contrast to source reaches, these channels receive most of their sediment load from upstream fluvial input rather than local erosion and hillslope processes. Response reaches are areas where, over long time scales (centuries to millennia), sediment has accumulated and been stored as alluvial valley fill (e.g. extensive floodplains or terraces). Since these are alluvial channels, built from river deposits, they are expected to more readily adjust their form ("respond") to changes in sediment input or flow intensity.

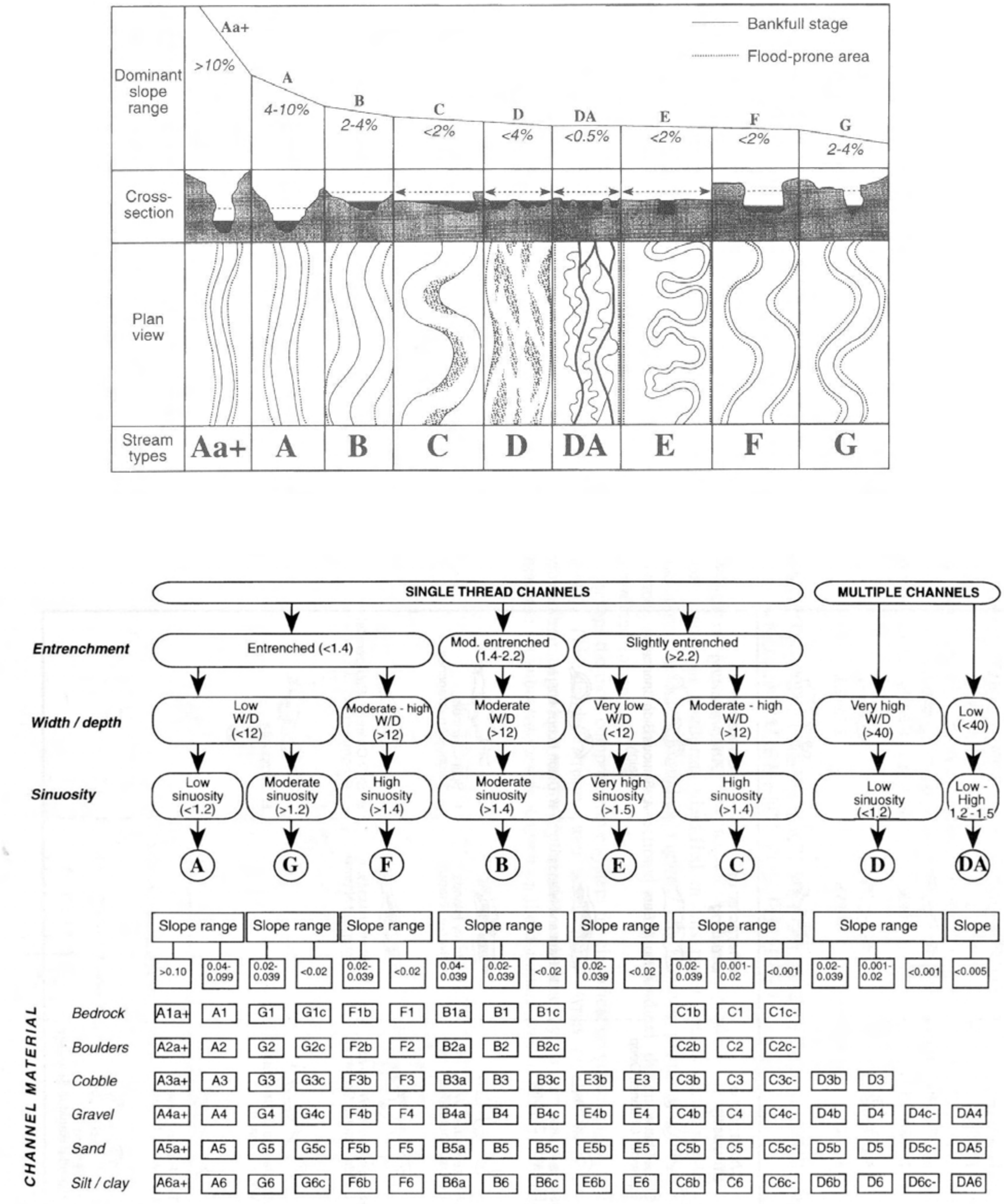



**Geomorphology Figure 2**: Montgomery and Buffington stream classification. Longitudinal view and watershed-scale process perspective. From *Channel-reach morphology in mountain drainage basins*, D. R. Montgomery and J. M. Buffington[21]. Reproduced with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1977 Geological Society of America.

Rosgen's classification system (see **Geomorphology Figure 4**) is comprised of eight basic channel types (A, B, C, D, E, F, G and DA), defined according to a dichotomous key, based on bankfull channel measurements. The variables used to classify the channel are multiplicity (single thread, multiple thread), entrenchment ratio (a measure of confinement), width/depth ratio, and sinuosity. Within each of the eight basic types, the channel is further classified from 1 to 6 according to dominant substrate (bedrock, boulder, cobble, gravel, sand, and silt/clay, respectively), and channel slope. To put the system in a landscape geomorphic perspective, Rosgen also describes 11 different valley types, each of which tends to harbor certain stream types by virtue of how the "valley" formed and its typical slope and sediment regime. Use of Rosgen's system is contingent on correct identification of bankfull, which was discussed earlier.




**Geomorphology Figure 3**: Montgomery and Buffington stream classification. Sketches of selected stream types. From *Channel-reach morphology in mountain drainage basins*, D. R. Montgomery and J. M. Buffington[21]. Modified with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1977 Geological Society of America.




**Geomorphology Figure 4**: Rosgen stream classification. From *Channel Types and Morphological Classification,* C. R. Thorne[23]. Copyright 1977. © John Wiley & Sons Limited. Modified with permission.

Since form and process in river systems are interdependent, Rosgen's system, although strictly defined according to morphology, can be used to infer dominant process characteristics. Rosgen's system has the advantage of being more quantitatively objective than Montgomery and Buffington's, and is in more widespread use nationwide.

To be useful to applied geomorphologists, any classification system should be based on a selection of the most important features that characterize physical processes. Certainly, energy (slope and confinement), and substrate characteristics (particle size, as related to ease of transport and hydraulic roughness) could be considered a minimum list of factors. The Rosgen system includes these factors, but use of these variables in other *ad hoc* classification schemes is sometimes desirable depending on project objectives.

## *1.5 Geomorphic Thresholds*

Short-lived states of disequilibrium often result when a geomorphic threshold is exceeded. A geomorphic threshold is a combination of the independent variables (such as described above) that results in a shift from one stable landform to another of a different type. This occurs at the moment in time and space at which forces and resistance to those forces are equal. The classic example of a physical threshold is the attainment of critical shear stress in a channel during increasing discharge. In such case, the channel bed remains immobile through increasing discharge until a threshold of shear stress is exceeded, upon which bedload sediment motion is initiated. An example of a geomorphic threshold is the conversion of a narrow, meandering channel to a wide, braided channel when destruction of streambank vegetation results in reduction in root strength and loss of soil surface protection. Accelerated bank erosion follows, and the channel grows wider and shallower until shallowness and splitting of flows reduces the force of erosion to match the new, reduced, erosion resistance. The result is a different channel morphology, which may then evolve slowly back to a meandering channel as vegetation recovers.

Both extrinsic and intrinsic geomorphic thresholds exist. An extrinsic threshold is exceeded by application of an external force or process, such as a change in sediment supply or discharge. Progressive change in the external force triggers an abrupt, physical change in the system. Examples of forces relating to extrinsic thresholds are climatic fluctuations, land-use changes, and base-level changes. For example, urbanization typically increases the frequency and magnitude of peak flows, which can overwhelm the resistance of the streambed and banks to erosion, causing an episode of down-cutting or incision (see below). By contrast, an intrinsic threshold is exceeded when system change occurs without a change in an external variable; the capacity for abrupt change is intrinsic to the system and can be considered within the system's natural variability. For example, an intrinsic threshold might be reached when the structural elements (such as wood, rocks, beaver dams or soil cohesion) holding a growing volume of sediment in storage within the floodplain weaken or lose effectiveness over time, causing an episode of channel incision[24].

The most significant controls on channel stability over a period of years or decades are flow regime, sediment supply, and vegetation. If any of these controls change (either progressively or suddenly), the channel may cross a threshold and undergo change. Channel avulsion, the formation of a new channel across the floodplain, and channel incision, the general lowering of channel-bed elevation, are two common types of channel changes involving geomorphic thresholds.

## 1.6 Channel Responses to Change in Dependent and Independent Variables

Rivers are complex systems of inputs and responses whose features and form are rarely constant. Explanation and prediction of their behavior requires great depth in understanding of historic condition and current morphology and process, at times involves considerable educated speculation, and is always uncertain and prone to risk. In spite of the complexity of predicting or explaining geomorphic response, there are a number of common generalized channel responses that can be attributed, at least theoretically, to distinct causes. These include aggradation, incision, lateral migration, and avulsion, which are most commonly observed in alluvial systems that are free to adjust their channel boundaries.

### 1.6.1 Aggradation

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation. Aggradation is a response to channel system changes that reduce the channel's capacity to transport the sediment delivered to it. Generally, this occurs as result of either increased sediment supply (load) or size (gradation), or diminished stream power (transport capacity).

Aggradation associated with increased sediment supply may occur in response to any of the following conditions:

- Increase in sediment size or volume associated with landslides, debris flows, or other geologic disturbances
- Increase in sediment volume inputs from hillslope disturbances including vegetation removal, fire, and agricultural and other land use impacts
- Increase in sediment volume inputs from excessive bank erosion
- Increase in sediment volume inputs from excessive bed erosion from channel incision upstream

Aggradation associated with decreased stream power may occur in response to any of the following conditions:

- Increased channel width resulting in decreased unit stream power
- Large dams reduce duration of transport discharge
- Diversions reduce discharge
- Split flow within a channel reduces discharge in each split channel
- Reduced channel slope associated with local dams or grade control placed above grade (beaver dams, log jams, culverts, etc.)

### 1.6.2 Channel Incision

Channel incision is the inverse of aggradation and involves the progressive lowering of the channel bed relative to its floodplain elevation. Incised channels (also called entrenched or incised channels) occur when stream power exceeds the channel bed's resistance, or when sediment output exceeds the sediment input to the reach.

Incision associated with decreased sediment supply may occur in response to any of the following conditions:

- Upstream dams may cause sediment "starvation"
- Removal of sediment from the channel
- Decrease in sediment delivery to the stream system

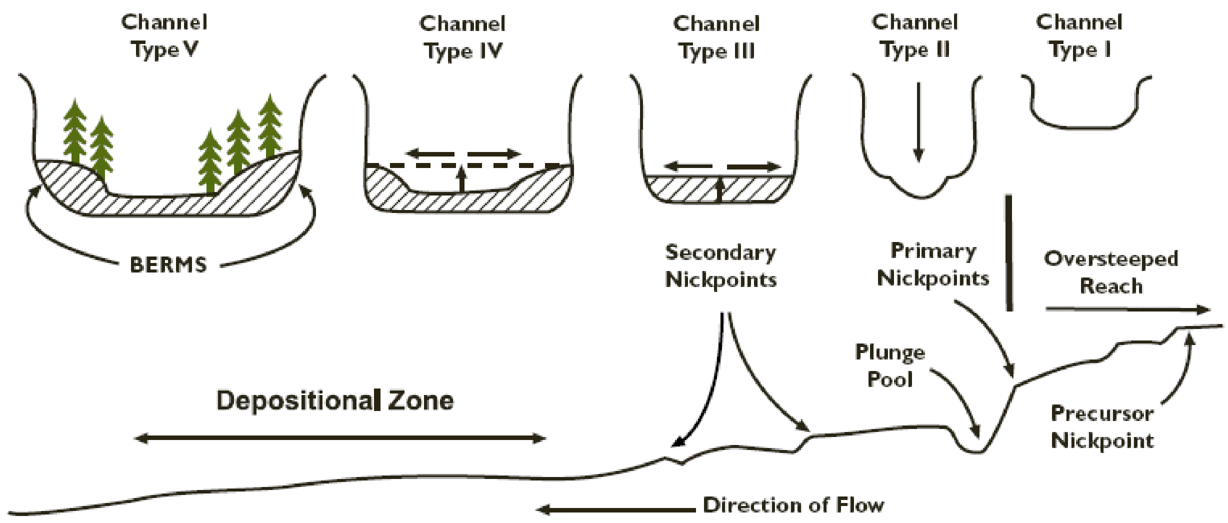
Incision associated with increased stream power may occur in response to any of the following conditions:

- Stream channelization and straightening causing a steepening of the channel profile
- Decreased channel roughness due to channelization, stream cleaning, large wood removal, and splash damming.
- Lowering of base level, such as the lowering of a lake, removal of grade control (culvert, bedrock, log controls)
- Increase in peak flows due to land use changes
- Increase in duration of transport flows associated with vegetation removal, urbanization, or other forms of land development that increases runoff rates and volumes
- Concentration of high flows within the channel due to encroachment of walls, structures, or levees
- Channel bed disturbance which disrupts the armor layer (push-up dams or gravel mining), which typically results in smaller bed substrate, and thereby reduces the stream power necessary to mobilize it
- Diversion of storm water or sewer discharge into the stream

Regardless of the causes of incision, the response pattern of incised channels is remarkably similar throughout a variety of stream environments. Incised-channel evolution models are useful for tracking landform development through time. Schumm and others [25], used such a model to develop a channel-evolution sequence for a stream in Mississippi. The model assumed that the base level for the channel did not change, and that land use in the watershed remained relatively constant. The model (see **Geomorphology Figure 5**) described five successive channel reach types whose conditions include Stable (Stage I), Incising (Stage II), Widening (Stage III), Stabilizing (Stage IV), and a new, dynamic equilibrium (Stage V).

This model portrays a very common phenomenon occurring subsequent to channel incision – channel widening. As a stream channel incises, its flow capacity increases and stream energy becomes concentrated within the channel, rather than dissipating on the floodplain. Additionally, bed erosion can destabilize stream banks by oversteepening the slope and undermining the bank toe, particularly after the level of the active channel incises below the root zone of the riparian vegetation, and/or after the channel erodes down to a more resistant substrate. The combination of increased energy within the channel and reduced bank stability often leads to rapid bank erosion.

Channel incision can result in a floodplain surface becoming high enough above the channel that it is no longer inundated by the current hydrologic regime (see **Geomorphology Figure 6**). The formation of such a perched floodplain, or terrace, disconnects that surface from the water table and affects the establishment and survival of riparian vegetation. Other effects include unstable banks due to over-steepening, bank instability due to groundwater discharge, increased shear stress because of low-probability flows being contained within the channel, and loss of wetland/floodplain habitat and backwater areas. This process is often coupled with the progressive formation of a new floodplain surface within the incised channel (i.e., channel recovery), unless, as often happens, the banks are armored to prevent further erosion.




**Geomorphology Figure 5**: Diagram of a channel evolution model. From *Fluvial processes and morphological thresholds in incised channel restoration,* M. D. Harvey and C. C. Watson[26]. Copyright permission is being sought.

**Geomorphology Figure 6**: Channel incision. An example of channel instability in an incising channel. Columbia Creek, Oregon. Photo provided courtesy of Inter Fluve, Inc.

For a complete discussion of channel incision and incised river channels, refer to:

- Darby and Simon, 1999[27].
- Knighton, 1998[28]
- Schumm, Harvey, and Watson, 1984[25]

### *1.6.3 Lateral Channel Migration and Erosion*

Channel migration is the progressive movement of a channel across a valley and involves bank erosion and transport of eroded materials. Lateral channel migration may occur within the context of equilibrium, provided that channel form does not change overall. In such cases, the width of the channel does not change – as a bank erodes laterally, a point bar develops across the channel, thereby maintaining channel form. However, lateral migration may also occur in response to disturbance or external changes in input variables resulting in widening of the channel and other changes in channel form.

Lateral migration may be initiated or exacerbated by the following conditions:

- Hardening of channel banks upstream or across the channel may reduce the channel's capacity to adjust locally, and may transfer the excess energy to an un-hardened area
- Channel aggradation
- Channel incision
- Riparian and channel bank vegetation removal reducing bank resistance
- Excessive saturation of banks during low flow periods due to irrigation
- Rapid drawdown and saturation failures related to dam releases

### *1.6.4 Channel Avulsion*

Channel avulsion is a process whereby a channel shifts its location by cutting across adjacent terrain. Avulsion occurs naturally in meandering streams, most commonly cutting off a mature meander bend during long-duration or extreme overbank flows. The occurrence of avulsion can also be brought about by channel manipulation, by armoring channel banks, or as a result of changes in external variables. The mechanism by which avulsion occurs is generally through headcutting and scour of a new channel through the floodplain. Floodplain slope is usually greater than channel slope, so for an equal flow depth, velocity and shear stress can be higher on the floodplain than in the channel. This is particularly an issue for wide shallow channels with active floodplains, because flow depth in the channel and on the floodplain can be very similar. This headcutting and scour may be initiated during overbank flows associated with large floods, logjams, beaver dams, or ice jams. Avulsion generally occurs when other channel conditions increase the volume of flow across the floodplain relative to the channel itself, thereby increasing the erosional forces on the floodplain. Aggradation within the main channel or a blockage of the main channel is the primary conditions under which flow energy increases on the floodplain. The reentry of floodplain flow to an incised channel will also promote headcutting and channel avulsion. On the floodplain, restrictions that concentrate flow or removal of vegetation that slows flow and provides resistance to erosion may result in energy conditions that lead to avulsion during overbank flows.

Avulsion occurs in numerous types of channels[29]. Highly sinuous meandering channels may avulse due to insufficient sediment transport, which results in channel aggradation and further loss of channel capacity. Under equilibrium conditions, this is part of the normal channel processes of meander development. The meander elongates due to erosion of the cut bank and deposition on the point bar; slope, velocity and sediment transport capacity are gradually reduced. During overbank flows, the differential between the slope of the channel and the slope of the floodplain eventually results in headcutting through the floodplain, causing a meander cutoff (creating a variety of habitat, including backwater habitat, oxbow lakes and wetlands). Multiple-thread channels with high loads of coarse sediment and debris are prone to blockage at the locations where flows split. This causes frequent shifting of the dominant thread, and less frequently, development of new channels across the floodplain as flows are forced overbank by in-channel aggradation. Finally, all channels are prone to avulsion if they become perched relative to their floodplain. This is common in alluvial-fan environments or along relocated channel segments.

## 2 Vegetation and Large Wood in Fluvial Process

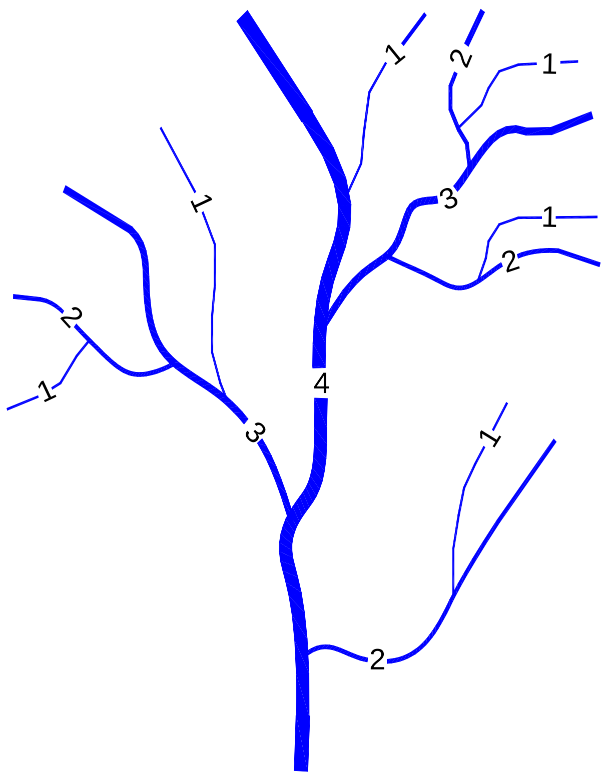
Vegetation affects the geomorphic process and resultant channel forms by increasing resistance to erosion of channel banks (riparian vegetation) and by interrupting and redirecting channel flow (in-channel wood). The character of riparian vegetation can act as a key independent variable in determining channel form and process. (The type of vegetation that occurs naturally is a function of geology, topography, and climate.) Riparian vegetation plays an important role in maintaining a stable channel form by stabilizing streambanks and dissipating energy along the banks in virtually all channel types throughout the Pacific Northwest. The growth of riparian vegetation in or near the channel also facilitates floodplain formation as vegetation increases hydraulic roughness, reduces erosion and promotes sedimentation. Some of the most tortuous meanders occur in streams dominated by sedges in meadow streams. Willows commonly stabilize newly deposited materials in bars and thereby facilitate the creation of new floodplain area. Upland vegetation also can play a role in channel process by controlling hillslope erosion, thereby reducing sediment input to stream channels.

Both upland and riparian areas also contribute vegetative debris to the channel. The role of large wood in channels is now recognized as a critical factor affecting geomorphology in forested environments and as a potential component of channel design[30][31]. Large wood in streams represents large roughness elements that divert flowing water and influence the scour and deposition of sediment in forested streams throughout the world. Large wood in stream channels results from trees that fall from banks or hill slopes. Processes that initiate tree fall include wind throw, bank erosion, channel avulsion, tree mortality, mass wasting and land-use practices such as logging.[32] The introduction of large wood into the channel affects both channel form and process by:

1. Creating steps in the longitudinal profile of the streambed (of steep, confined channels), thus dissipating energy, aiding in formation of both pools and riffles, and increasing sediment storage[32];
2. Locally reducing channel gradient (i.e., above the log jam), thereby capturing a finer class of sediment than would otherwise deposit in the channel;
3. Increasing in-channel hydraulic complexity, thereby increasing channel habitat complexity;
4. Improving fish habitat by increasing types and sizes of pools[33] (pools associated with wood may be deeper and have more depth variability than free-formed pools[34]);
5. Inducing hydraulic head differential to promote hyporheic flow;
6. Forming channel bars and creating inducing sorted gravel deposits important to spawning (this influence has not been extensively studied)[35];

7. Promoting sediment deposition along the active channel and floodplain, which provides sites for riparian vegetation colonization, the growth of forested islands in the channel and forest floodplain development;[36]
8. Retaining small wood and organic detritus;
9. Promoting floodplain connectivity and periods of inundation by increasing channel roughness; and,
10. Stabilizing backwater and side-channel areas (chute cut-offs and oxbows).

The geomorphic effects of wood vary with stream size. In low-order, headwater streams (first and second order), large wood often spans the channel, or, if submerged, induces local sediment storage and steps in the water surface profile. In mid-order streams (e.g. third and fourth order), large wood is large relative to the stream and may cause significant channel migration or widening along with sediment storage. In high-order streams (e.g., forth or fifth order) (see **Geomorphology Figure 7**), where large wood is small relative to the channel, wood accumulations may increase channel migration and the development of anastomosing or secondary channels, although islands formed as a result of large woody deposits may actually be quite stable[32].




**Geomorphology Figure 7**: Stream order. First order streams are headwater streams. As headwater streams combine to form larger streams, the order increases.

# 3 ASSESSMENT METHODOLOGIES

## *3.1 Baseline Geomorphic Analysis: Evaluation of Existing Conditions and Historic Change Where Restoring Historic Configuration is Appropriate*

The most important components of geomorphic analysis include:

- Assessment of past channel change,
- Determination of causes of channel change,
- Assessment of current channel conditions, including morphology, stability and departure from conditions expected for the given stream type,
- Assessment of probable future channel evolution,
- Reduction of uncertainty in key assumptions regarding management, design, processes or conditions, or effects on habitat or critical species

Habitat restoration, streambank protection, and other instream construction projects will likely be unsuccessful if the driving forces of channel adjustments are not recognized and addressed. Consequently, projects designed to mimic or alter natural channel processes require an understanding of the causative agents of change.

### *3.1.1 Characterizing Existing Channel Conditions*

The initial characterization of the project reach should be based on plotted bed and floodplain profiles and maps or aerial photographs that show channel planform. The project reach should be described in terms of channel slope, pattern, sinuosity, and cross-sectional dimensions. Infrastructure controls should be identified and their geomorphic relevance indicated, such as fixed-bed elevations (pipelines, weirs, bridge aprons) or areas of channel or floodplain encroachment (roads, development, bridges, culverts, levees).

#### 3.1.1.1 Channel Longitudinal Profile

Channel slope is defined as the vertical fall of a stream over a given distance. It is typically reported as a percentage (ft/ft) or as feet of drop per mile (ft/mile). Channel profiles (elevation vs. distance plots) depict slope trends on a stream system. The most accurate means of determining the slope of the channel is by surveying the channel thalweg elevation (the deepest thread in the channel bed), the water surface, and the elevation of bankfull (best, if possible) or other high water indicators through a reach (such as "ordinary high water"). Longitudinal profiles may sometimes be obtained from the Federal Emergency Management Agency if a hydraulic model has been developed for flood-insurance studies. Channel profiles determined from topographic maps may provide approximate channel slope, but will not be detailed enough to provide a longitudinal profile since the scale of the contour lines is generally too coarse, and for smaller streams may actually represent the canopy cover. Furthermore, topographic maps are based on survey data that may predate significant changes in the valley topography and the channel.

Channel slope is always measured in terms of the channel distance, rather than the valley distance, and can be calculated by the following equation:

$$S=(E_2-E_1)/D$$

Where, S = channel slope, $E_2$ and $E_1$ = bankfull elevations (or water surface, in feet or meters) at two similar geomorphic points along the thalweg, and D = channel distance between $E_2$ and $E_1$ (in feet or meters). A more accurate representation of channel slope will be attained if survey points are located from the top of one riffle to the top of another riffle (thereby including the entire channel unit), rather than between a riffle and a pool. By surveying the beginning, middle and end point of each channel unit, the riffle slope and pool slopes can be determined, as well as maximum and average riffle and pool depths if the thalweg is surveyed as well. Ratios of maximum to average depth can then be compared to expected regional means as a tool to detect departure from stable conditions. The longer the survey length, the more accurate the slope calculation will be. If a significant valley control is crossed, the survey should be analyzed as two distinct reaches.

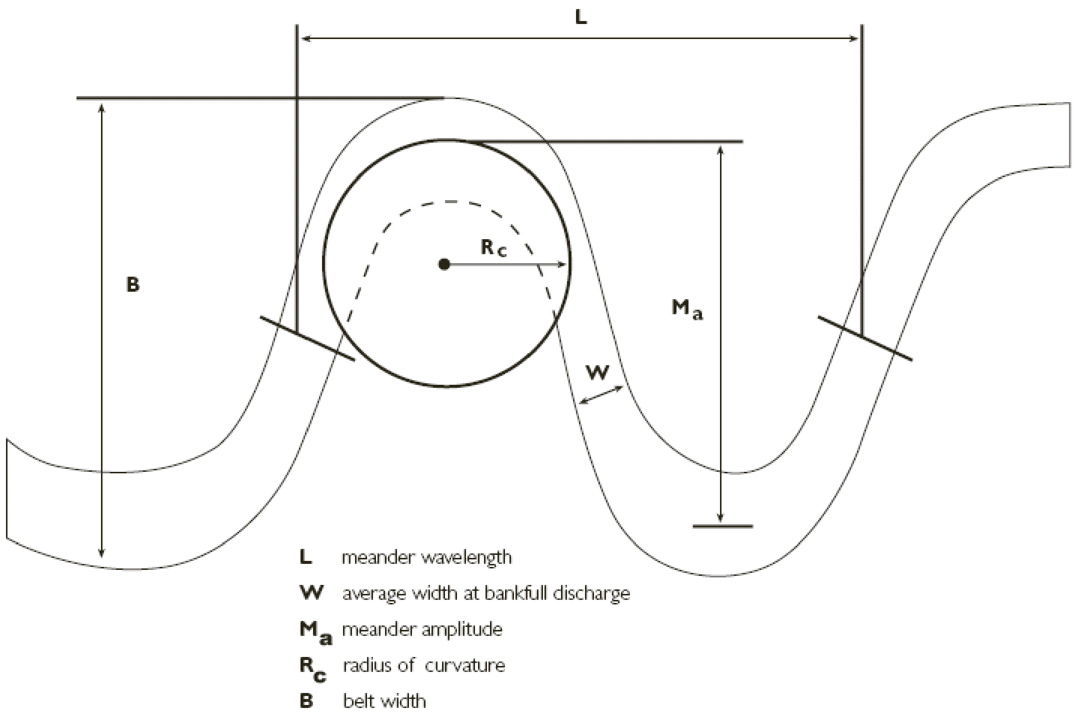
#### 3.1.1.2 Channel Planform

Channel planform is the form of a stream as seen in map (aerial) view. In streams with meandering patterns, planform is quantitatively described in terms of sinuosity by the equations:

$$P = D_c / D_v \text{ or}$$
$$P = S_v / S_c$$

Where P = sinuosity, $D_c$ = channel length (feet or meters), $D_v$ = valley length (feet or meters), $S_c$ = channel slope, and $S_v$= valley slope. Channel length is theoretically best measured along the channel thalweg or, if necessary, the centerline, but can be measured along one bank or the other for small channels.

Other parameters that describe channel planform are the belt width, wavelength, amplitude, and radius of curvature of an individual meander bend (**Geomorphology Figure 8**). Collectively, these planform characteristics can be compared to historical conditions in order to assess channel behavior over time, and to expected ranges of values for channels of the same type in the same physiographic province. Radius of curvature is particularly important, as overly sharp radii greatly increase the near-bank shear stress and erodibility.

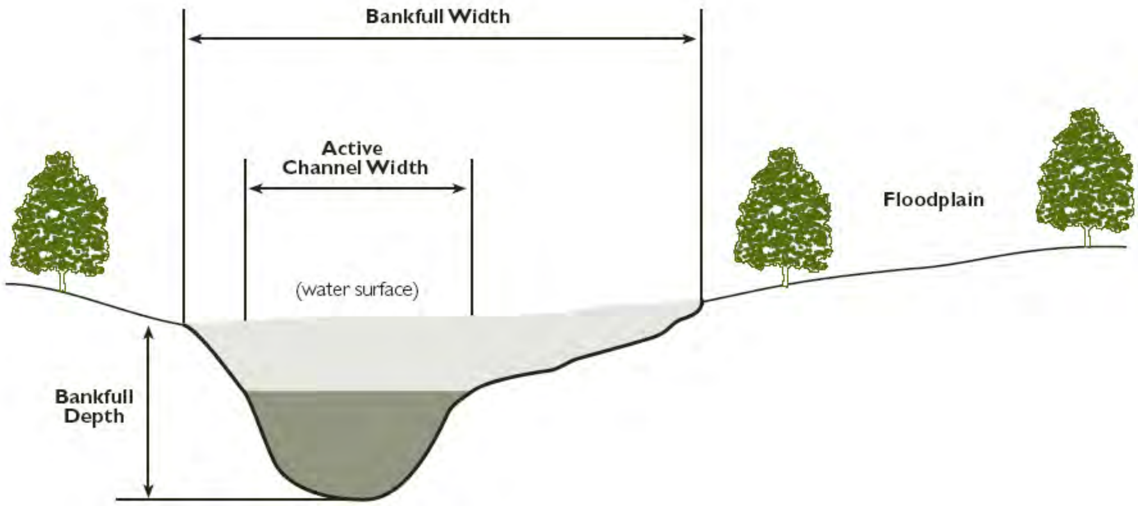



**Geomorphology Figure 8**: Channel planform characteristics.

### 3.1.1.3 Channel Cross-Section

Channel cross-section reflects the two-dimensional view across the channel, typically viewed in the downstream direction. A set of surveyed cross-section points should include, at a minimum, terrace elevation, floodplain elevation, top of bank, bank toe, lower limit of vegetation, and thalweg, with enough intervening points to define the shape of the channel. The ends of the cross-section should extend far enough up to define at least some of the important peak flows, although the level of detail can be coarser above bankfull. Typically, the elevation at twice the maximum riffle bankfull depth will encompass the 50-year flood[37]. In the Rosgen classification system, the zone delimited by twice the bankfull depth is called the "flood prone area," and is used to define the entrenchment ratio ($W_{fp}/W_{bf}$, where $W_{fp}$ = flood prone area width and $W_{bf}$ = bankfull width). Typical dimensions measured from a channel cross-section include bankfull width, bank height, bank slope, and channel maximum and average bankfull depth. By convention, the right and left banks reflect the sides of the channel as viewed in the downstream direction (**Geomorphology Figure 9**).

In addition to the full cross-sections, width, bank height and thalweg depth should be measured at multiple locations in the reach to characterize the range of variability of pools and riffles. From these locations, a smaller number (minimum: one riffle, one pool, and one pool tail-out zone or other area likely to show response) can be selected that are deemed "typical."



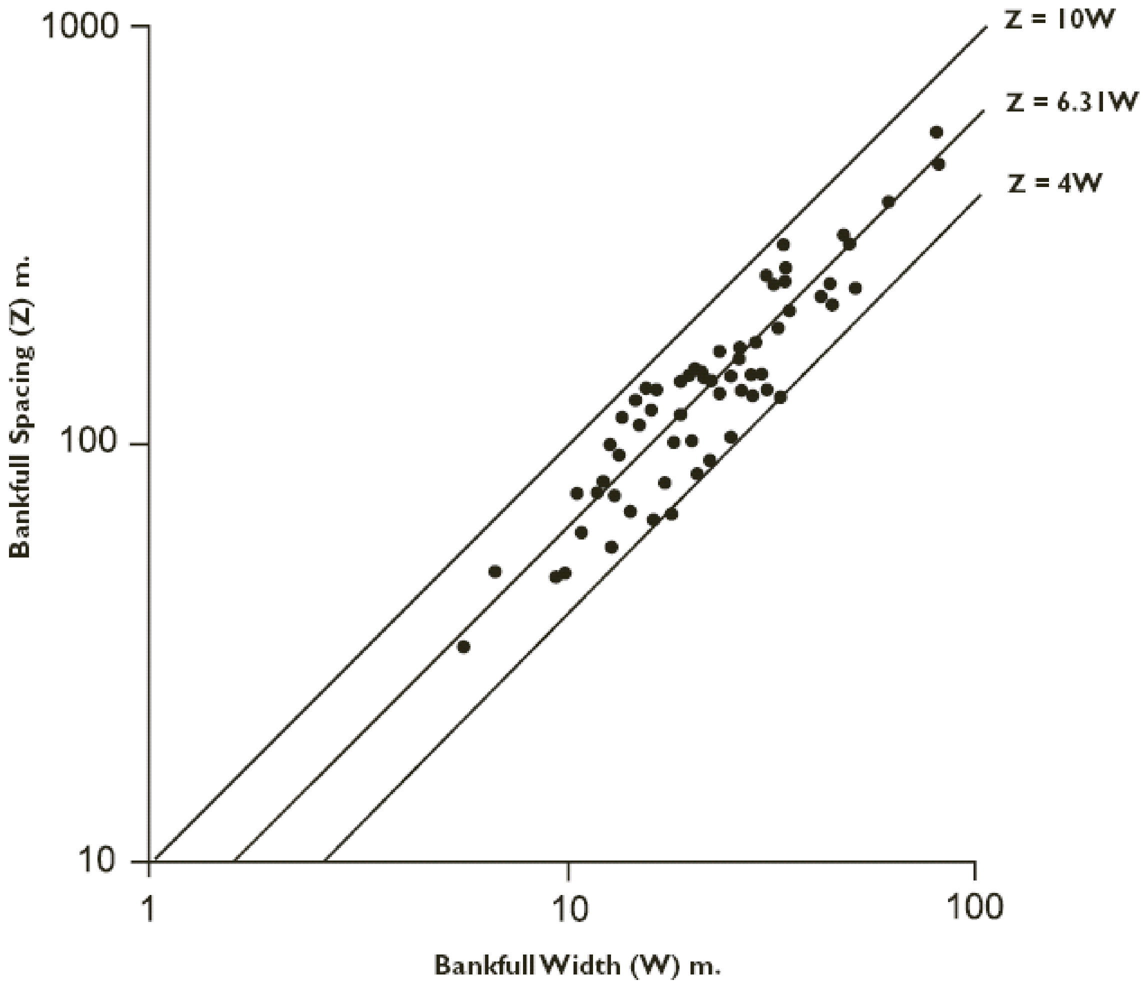

**Geomorphology Figure 9**: Channel cross-section.

### 3.1.1.4 Pools and Riffles

Pools and riffles generally occur at relatively constant spacing in alluvial streams. A pool-riffle sequence is a dynamic response of the channel to a large-scale, non-uniform distribution of three variables: velocity, boundary shear stress and sediment[38]. Leopold and others[39], determined that riffle spacings were consistently on the order of five to seven times the channel width (**Geomorphology Figure 10**). This empirical deduction is consistent with a theoretically predicted spacing of 2π (6.28) times the channel width determined by Hey[40]. Hey and Thorne[41] further substantiated the correlation between width and riffle spacing, predicting riffle spacing as:

$$z = 6.31\ W_{bf}$$

where z = the distance of riffle spacing (meters), and $W_{bf}$ = bankfull width (meters)[41]. This definition of riffle spacing is based on work in Great Britain on gravel bed rivers with single-thread channels and a mix of straight, sinuous, and meandering planforms. The coefficient of determination for this data set is 0.88, and the overall range of riffle spacing for the majority of sites is between four and ten times the channel width[41]. Along with pool-riffle spacing, the average and maximum pool and riffle depths, and the ratios of maximum to average depths can be obtained from the longitudinal profile. All of these factors become clues to departure from stable or expected morphology, and ways to track changes over time.




**Geomorphology Figure 10**: Riffle spacing as a function of bankfull width. From *Fluvial Processes in Geomorphology*, L. B. Leopold, M. G. Wolman and J. P Miller[39]. Copyright permission being sought.

### 3.1.1.5 Substrate Analysis and Sediment Transport

Assessment of sediment transport processes requires quantitative information on streambed substrate. The most accurate way to do this is with a volumetric sample taken from a location judged to be typical of the active alluvial material. Sometimes, this can be obtained from a dry gravel bar, but more often it requires instream sampling of an alluvial bedform. The surface layer is gathered and sieved separately from the subsurface layer, yielding a particle size distribution (percentage in each size class) for each stratum. Size distributions are based on the logarithmic Phi (powers of two) scale. That is, 1 – 2 mm, 2 – 4 mm, 4 – 8 mm, etc. The size distributions of the surface and subsurface, and their relationship, provides quantitative information about the average sediment load volume and size, the critical shear stress for bed mobility, fine versus coarse sediment sources, hydraulic roughness, spawning habitat quality, and hyporheic flow potential. From these size distributions, sediment benchmark parameters such as the median size ($D_{50}$), 84th percentile ($D_{84}$), percentage of fines and maximum particle size ($D_{100}$) are determined.

Some investigators prefer to assess sediment using a pebble count procedure, such as the 100-point Wolman pebble count or the more statistically-defensible 400-point grid sample. Pebble count information is useful for assessing hydraulic roughness, for characterizing the maximum-sized alluvial particle (called the dominant particle), and for channel classification in some systems (e.g. Rosgen classification). For these applications, the pebble count may be superior to the volumetric sample, since a more extensive area on the bed can be sampled. However, for sediment transport assessment (including critical shear stress) or assessment of percentage fine sediment, the pebble count is not recommended, since it is biased against particles smaller than the human fingertip, which can represent a significant portion of the sediment load even in gravel or cobble-bedded streams. Substrate and sediment transport analysis are covered in the *Sediment Transport* appendix.

### *3.1.2 Channel Classification*

A classification of stream reaches can aid in visualizing and describing the project site[23]. Channel classification can also aid in deciding which channel morphology, and consequently what array of project design possibilities, are appropriate to the geomorphic or valley setting. Furthermore, classification serves as a tool for assessing the sensitivity of the channel to human modification or natural disturbance, and the risk of project failure. Finally, in some types of projects, such as channel modification, the use of natural analogs ("reference reaches") requires matching of similar channel types, which in turn requires consistent channel classification.

Which system is used is largely a matter of professional judgment. The systems of Rosgen[22], and of Montgomery and Buffington[42] have been described previously. Each of these systems requires some formal training and practice for consistent application. Sometimes, it is desirable to develop an *ad hoc* classification system, such as when the stream of interest not well described by existing schemes (e.g. estuaries).

It is important to note that most classification systems are based on the existing channel morphology of a stream, which may or may not be in equilibrium. In other words, they best describe only existing conditions, not historic conditions or the functional potential of a stream system. A classification system must be used with the understanding that fluvial systems are constantly adjusting and evolving in response to changes in slope, hydrology, land use and sediment supply.

### *3.1.3 Assessing Historic Channel Change*

#### 3.1.3.1 Aerial Photography and Historic Maps

When available, sequential aerial photos of a stream channel provide a historical record of channel planform changes. Sequential air photos are often available dating back to the 1930s, while other historic photos can sometimes be found in historic archives dating back to the last century. Historic land survey maps often show details of river location and form as well. This information, coupled with hydrologic data from stream gages, is extremely valuable for understanding how the particular channel responds to floods. An evaluation of historic channel change may reveal previous channel conditions that provided quality habitat or channel stability, which may then be used as the basis for project objectives. However, an aerial photo provides a snapshot in time and does note necessarily imply channel stability. The stream may have been responding to significant changes in the watershed, or may have been stable under different watershed conditions. Early photography from the 1930s represents a period of significant landscape alteration (grazing and timber harvest) that often exceeds current disturbance levels. There is no reason to assume that a past morphological form will be stable under current hydrologic and landscape conditions unless watershed conditions have remained relatively constant, which is rarely the case.

Aerial photographs for the western United States are recorded in a database maintained by the U.S. Geological Survey Earth Science Information Center (the USGS will search for historical photography at *1-888-ASK-USGS*). Access to maps and photographs produced by USGS can be found at http://mapping.usgs.gov. Aerial photographs of your region can be obtained from the Washington State Department of Natural Resources, the Washington State Department of Transportation, the Federal Bureau of Land Management, the U.S. Forest Service, the U.S. Army Corps of Engineers and the Natural Resources Conservation Service.

#### 3.1.3.2 Ground Reconnaissance

Field observations provide valuable information regarding flood history and channel response. This information is especially valuable when combined with hydrologic data regarding flood-recurrence intervals – for example, the effects of a recent 10-year or 25-year recurrence-interval event might be directly observed in the field. Ground assessment of stream channels may include observable flood impacts, such as abandoned channels, natural channel cutoffs or the accumulation of wood on mid-channel bars. Many geomorphic channel features can be roughly dated according to the age of riparian vegetation that is present. For example, an abandoned side channel with 10-year-old cottonwoods present may represent the impacts of a flood documented 10 to 11 years ago. Ground reconnaissance is an essential part of a geomorphic assessment and can provide useful information on the geomorphic effects of large flows in a particular channel reach.

Another important tool available for geomorphic assessment is the observations of long-time residents and others who have been involved with the system over time. Local historical societies often have collections of photos for various streams in their area, which provide general information on riparian vegetation and potentially other stream attributes. When assessing the reliability of anecdotal accounts, consider that memory of specific numbers representing dates, water levels, water extent, etc. is highly fallible. However, memories that are tied to specific activities or informal physical benchmarks (e.g. walls of buildings) may be very accurate.

### *3.1.4 Channel Stability Analysis*

Channel stability is assessed by measurements capable of detecting excessive bank erosion, excessive streambed erosion or scour, or excessive deposition. Here “excessive” means outside the expected range of variability for the given stream type and setting. If excessive erosion or deposition is occurring, the channel is in a state of transition from one type to another, i.e. it is changing its basic shape, pattern and/or longitudinal profile. Vertical instability (incision or aggradation) is often coupled with lateral instability (excessive bank erosion and accelerated channel migration or avulsion rates).

Channel incision is commonly indicated by:
- headcuts or knick points, which are steep breaks in channel longitudinal profile.  In coarse-bedded streams, headcuts are more subtle (spread out) than in fine-textured systems, and often require a longitudinal profile for definitive identification.
- Over-steepened or vertical banks with evidence of  gravitational failure (geotechnical instability, as opposed to surface erosion)
- Previous engineering activities such as extensive channel armoring
- Conversion of moist-site vegetation to dry-site vegetation as the floodplain becomes "perched" and the water table falls

Channel aggradation may be indicated by:
- Pool infilling (often, a mass of finer material may reside over an older, buried coarse pavement layer)
- Excessive overbank deposition, especially, overbank deposits of medium or coarse gravel as opposed to sand and silt
- Fresh avulsions
- High width to depth ratio where a lower ratio is expected
- Excessive mid-channel bar formation, or transverse bars that direct flow into the streambank
- Excessive locally-derived large wood recruitment
- Substrate characteristics indicative of high bedload (poorly developed pavement layer, matrix-supported subpavement layer, buried pavements, sand dunes or other bedforms in a coarse-bedded stream)

Lateral instability can be assessed by indices that quantify near-bank shear stress and bank erosion potential, such as Rosgen's Bank Erosion Hazard Index, by width to depth ratio, and by measured bank erosion rates from surveys (bank pins, toe pins, or cross-sections) or aerial photos.

## 4 Summary

A geomorphic assessment of a reach where habitat restoration, instream engineering work, or streambank stabilization projects are intended will provide quantitative understanding of the processes that continue to shape the channel over time.  Any geomorphic assessment should have clearly defined objectives, and the information gathered and analyzed should address these objectives.  Geomorphic analysis allows projects to be designed in such a way as to account for, and work with, natural processes.  This greatly improves the chances for project success, and reduces the need for costly maintenance or unanticipated repairs or retrofits.  Finally, accountability to the public that aquatic habitat and river corridors are being managed competently demands a higher degree of certainty in analysis and design than was once the norm, which can only be obtained by collection and analysis of physical process data.

## 5 Glossary

*Active channel* -- The active channel is that portion of the channel within the bankfull channel that is defined by the lower limit of perennial vegetation.

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