

Channel Migration Processes and Patterns in Western Washington

**A Synthesis for Floodplain Management
and Restoration**



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A Synthesis for Floodplain Management and Restoration

by

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Abstract

In unconfined valleys of Western Washington, lateral migration of stream channels is the primary physical process that creates biodiversity on floodplains. This channel migration also presents a hazard to adjacent communities and infrastructure. These costs and benefits of channel migration make it a central consideration in floodplain management and restoration. The Washington State Shoreline Management Act and Guidelines require that communities map Channel Migration Zones (CMZs) in order to evaluate the area likely influenced by migrating channels. This document explains channel migration processes and stream channel patterns in Western Washington, providing a succinct and readable summary of scientific concepts relevant to floodplain management and restoration.

Channels migrate across floodplains through processes of channel expansion, bend migration, and channel avulsions. Different combinations of these channel migration processes create distinct channel patterns. Channel pattern is the form of a channel as described from overhead. The major channel patterns of the Western Washington discussed here include the meandering, anabranching, and braided classifications. Meandering channels are characterized by a single, sinuous channel. Anabranching channels have multiple active channels separated by forested islands and floodplain surfaces. Large wood in channels form logjams that stabilize islands and sustain the anabranching pattern. Braided channels have multiple channels at low-flow that switch frequently, and become a single channel during high flows. This document and supporting conceptual models lay out the: (1) landscape controls on channel migration processes; (2) fundamental channel migration processes; and (3) channel patterns and the suites of channel migration processes that sustain them.

Introduction

Channel migration is the process by which stream channels move and shape floodplains through time (Wolman and Leopold, 1957). By virtue of its ability to recruit wood to channels, structure floodplain landforms, and create new ground for vegetation to establish, channel migration is the primary physical process in valley bottoms that creates habitat for aquatic organisms and terrestrial species (e.g. Ward and Stanford, 1995). In addition to ecological benefits, channel migration commonly threatens infrastructure like roads, homes, levees, and waste water treatment plants through its ability to erode large areas of floodplains and adjacent areas.

Human development in channel migration zones (CMZs) often results in significant economic impacts associated with property loss and costs of erosion protection measures. Efforts to limit channel migration and protect development are not only expensive, but can adversely impact fluvial ecosystems, worsen downstream flooding, and induce damage to adjacent or across-channel property. Further, channel migration into developed areas can introduce waste and contaminants into channels which impact water quality far downstream (Walling et al., 2003).

Erosion by migrating channels is linked to processes of water runoff, sediment transport, earth materials and vegetation that also control a channel's form and pattern. Channel form as observed from above is referred to as channel pattern. In unconfined valleys with broad valley bottoms, channel pattern ranges from a single, stable channel to multiple channels that switch with each passing flood (Leopold and Wolman, 1957). Differences in channel pattern are in part related to a channel's ability to manipulate its floodplain through vertical and lateral erosion, which result from the characteristics of the sediment it carries, its flow regime, the geology of valley and watershed, riparian vegetation, and the wood material entering the channel (Montgomery, 1999).

Streams in Western Washington display a variety of channel patterns dictated by variation in watersheds and floodplains spanning a range of geology, climate, topography, and land-use patterns (Beechie et al., 2006). The valley bottoms of these streams typically contain the greatest biological diversity and productivity within their watersheds, which is in-part due to their propensity for flooding and erosion. Due to their correspondence to aquatic and terrestrial habitats, as well as implications for flood hazards, the range of channel migration processes, migration rates, and patterns are of major concern to resource managers and land-use planners.

Purpose and Intent

The diverse landscape, climate, and geology of Western Washington create a variety of channel migration processes and patterns, which in turn correspond to varying levels of riverine habitat and hazards (Beechie et al., 2006). While a large body of scientific literature on streams and rivers of the region exists, a more general synthesis of the channel migration processes and patterns of Western Washington streams is needed. This document provides an accessible resource to planners, land-use managers, and floodplain managers seeking a general understanding of the patterns and processes of streams. The document describes the: (1) landscape controls on channel migration processes; (2) fundamental channel migration

processes; and (3) channel patterns and the suite of channel migration processes that sustain them.

This document does not provide prescriptive recommendations for floodplain management and restoration. It does, however, provide a succinct and readable summary of channel migration processes and channel patterns that serves as a conceptual basis for floodplain management and restoration decisions. While geomorphology is becoming an increasingly popular field, many professionals involved in floodplain management and restoration may lack formal training in the field. While this document cannot completely fill that gap, readers will be better equipped to think about floodplain problems in a way that considers geomorphic processes rather than rigid definitions and classifications.

Channel migration and shoreline management

Recognized as a fundamental element of the landscape, CMZs can provide a vital corridor for safely routing floods, protecting fish and wildlife, protecting water quality, and enhancing the view shed, recreation opportunities, and quality of life in local communities. The substantial economic, environmental, and public safety benefits underscore the importance of understanding, delineating, and carefully managing CMZs. The safest flood protection, and usually the least expensive option, is to limit development to areas not susceptible to either flood inundation or channel migration, thus eliminating exposure to channel migration hazards. For existing communities it is important to know whether they have areas within a CMZ so they can plan accordingly. Where defenses are needed, the most effective measures will accommodate some channel migration (e.g. levee setbacks) and dissipate the river's erosive energy (e.g. rough versus smooth revetments).

The National Flood Insurance Act of 1968 was the first legislation to recognize flood hazards and mandate mapping of flood inundation risks, but it includes nothing about erosion risks. Channel migration can impact areas outside of mapped FEMA floodplains and is often more damaging than flood inundation. Despite this, there is yet to be legislative recognition of erosion hazards with a mandate to map CMZs. To address this gap in federal policy, in 2003 Washington State required communities to delineate CMZs under the 1971 Shoreline Management Act (SMA).

The SMA directed the Washington Department of Ecology (Ecology) to develop appropriate administrative rules and provide assistance to local communities for developing Shoreline Master Programs (SMPs) and ordinances for both freshwater and coastal areas. The revised SMP Guidelines adopted in 2003 require communities to delineate CMZs to protect ecological functions and reduce hazards along streams. The SMP Guidelines specify that, during the watershed characterization and inventory phase of their SMP update, local communities will identify the general location of CMZs using relevant and reasonably available information (Washington Administrative Code (WAC) 173-26-201(3) (c) (vii)). WAC 173-26-221 identifies information that should be considered in CMZ mapping:

The channel migration zone should be established to identify those areas with a high probability of being subject to channel movement based on the historic record, geologic character and

evidence of past migration. It should also be recognized that past action is not a perfect predictor of the future and that human and natural changes may alter migration patterns. Consideration should be given to such changes that may have occurred and their effect on future migration patterns.

The SMA also directs Ecology to provide the scientific basis for and technical assistance on delineating regulatory channel migration zones for the SMPs (RCW 90.58.05). In accordance with these obligations, Ecology has developed tools for communities to evaluate channel migration across the landscape. This document is the most basic of these tools: a summary of channel migration processes and patterns in Western Washington that can help one gain an understanding of the fundamental science of channel migration, and conceptualize which and in what ways channels are prone to migrate. This document supports Ecology publications describing CMZ mapping methods referenced in the “Further Reading” section at the end of this report.

Landscape Context

Where, which, and how quickly geomorphic processes occur are products of the general structure and character of watersheds and landscapes. Landscapes can be divided into process domains, in which particular combinations of geomorphic processes operate (Montgomery, 1999). Because fluvial geomorphic processes directly influence aquatic habitat on floodplains, the distribution of process domains along stream channels also corresponds with variation in ecosystem processes and function. This report focuses on the process domain defined by unconfined, alluvial valleys (valleys with broad bottoms composed of sediment) which allow channels to migrate across their floodplains (Montgomery and Buffington, 1997; Church, 2002). The report further subdivides this process domain by channel patterns, which are sustained and characterized by different combinations of channel migration processes (Figure 1).

Systematic downstream changes in the dominant geomorphic processes put migrating channels into a landscape context (Vannote et al., 1980). The upper portions of stream networks often drain and transport sediment eroded from mountainous watersheds, where channels run through narrow valleys confined by bedrock walls. As well as limiting channel migration, confined valleys closely connect channels to hillslopes so that catastrophic processes such as debris flows and landslides commonly disturb and deliver sediment to channels (Grant and Swanson, 1995). Coarse sediment delivered from hillslopes is often too large to be transported by stream flow, so a large portion of sediment is transported by debris flows traveling along channels.

Moving downstream in the drainage network, valleys widen and have decreasing connection to valley hillslopes. As a result, much of the sediment transported through large channels with wide valleys is delivered from upstream reaches rather than adjacent hillslopes (Montgomery, 1999). Sediment size and quantity therefore depend on the stream’s capacity to carry sediment. As a result, streams become the primary agent shaping valley bottoms through erosion and deposition (Wolman and Leopold, 1957).

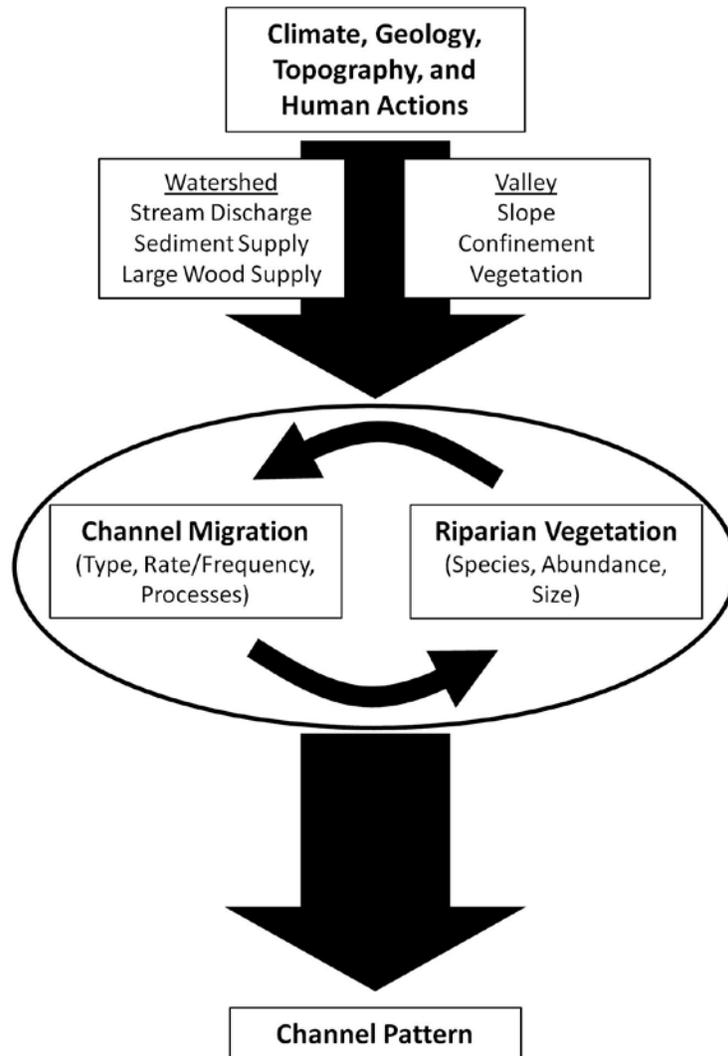


Figure 1. Landscape controls, channel migration processes, and channel pattern. Climate, geology, and topography are fundamental controls, and human actions have altered landscapes in a fundamental way. Over the watershed, they control stream discharge and supplies of sediment and large wood, which in turn control channel migration processes and their interactions with riparian vegetation. Climate, geology, topography, and human actions also dictate valley slope, confinement, and vegetation patterns, which also govern channel migration processes and riparian vegetation characteristics. Channel migration processes and riparian vegetation interact on the floodplain to create distinctive channel patterns. Human actions such as forest clearing, development, channelization, dams, and levees can have pronounced impacts on channel and floodplain processes. Because these actions influence most of the historic record of many rivers, drawing conclusions about channel dynamics from historical sources can be misleading, so it is important to know how humans have altered a given watershed or floodplain.

Geology, climate, and topography vary across a range of scales, which also controls the distribution of process domains across the stream network (Montgomery and Buffington, 1997; Montgomery, 1999) (Figure 1). These fundamental controls, as well as the human actions, influence factors like sediment supply, stream discharge, land-surface slope, and vegetation, which are important variables determining the form and processes of channels (Lane, 1954). Region-wide physiographic features such as the Cascade Range or Puget Sound Lowland have

geologic, climatic, and topographic characteristics which influence the broad-scale distribution of process domains (Montgomery and Buffington, 1997; Montgomery, 1999). For example, stark changes in precipitation and temperature occur across the Cascade Range which in turn create differences in stream flow and vegetation type. Similarly, sediment supply to streams commonly corresponds with the proximity to volcanoes along the Cascade Range due to volcanoes' high relief, glaciation, and erodible bedrock (Czuba et al., 2011). Even finer-scale variations exist as a result of local changes in climate, geology, and topography such as a local bedrock unit controlling the width and slope of a valley.

Climate, geology, and topography also dictate the physical and biological characteristics of a valley bottom (Montgomery, 1999) (Figure 1). Valley slope controls the overall capacity for a stream to erode its floodplain, a process required for channels to migrate (Nanson and Croke, 1992). The overall slope and topography of floodplains and valley bottoms result from landscape evolution that is the cumulative result of gradual and catastrophic processes of erosion and sedimentation that have occurred over geologic timescales. Geologically, the Pacific Northwest is a very young landscape that is rapidly evolving. For instance, the Puget Sound lowlands and adjoining alpine valleys were largely shaped by continental glaciers that receded approximately 14,000 years ago and the subsequent post-glacial reforestation - factors that control the present-day distribution of channel patterns and processes (Church and Slaymaker, 1989; Booth and Hallet, 1993; Collins and Montgomery, 2011).

On the floodplain, channel migration processes and riparian vegetation interact to form channel patterns with distinct landforms and characteristics (Figure 1). Channel migration recruits riparian trees to channels and creates new surfaces where vegetation subsequently germinates (Hickin and Nanson, 1975; Hickin, 1984). Vegetation also stabilizes banks and limits bank erosion (Thorne, 1990; Abbe et al., 2003; Micheli et al., 2004), which in turn can influence channel pattern (Gran and Paola, 2001; Braudrick et al., 2009). Wood can directly influence channel gradient (e.g. Keller and Tally, 1979; Abbe and Montgomery, 2003), and floodplain topography (Abbe and Montgomery, 2003; Montgomery and Abbe, 2006; Collins et al., 2012), which impact rates of vertical and horizontal erosion. In addition, logjams allow forested islands and multi-thread channels to form (Sedell and Froggatt, 1984; Abbe and Montgomery, 1996; Sear et al., 2010) and induce, mediate, and influence the pattern of channel avulsions (Montgomery and Abbe, 2006; Collins et al., 2012).

Channel Migration Processes

Channel migration occurs through processes of channel expansion, gradual bend migration, and abrupt channel switching called avulsions (Knighton, 1998). While the physical mechanisms of each migration process are different, the processes are often intertwined (Figure 1). For instance, avulsions occurring across meander bends (meander bend cutoffs) are often a direct result of gradual bend migration changing the geometry of channels. Gradual channel migration and abrupt avulsions therefore can be considered together under the overall process of channel migration. Channel widening can occur episodically in response to floods (Konrad, 2012) or as a long-term change due to increases in surface water runoff resulting from upland development or

climate change. It can also occur because of riparian vegetation removal (e.g. Brooks and Brierley, 2002; Brooks et al., 2003; Eaton, 2006).

Channel bend migration

A fundamental process of channel migration is the gradual migration of channel bends occurring as stream flow erodes one bank and deposits sediment along the other (Leopold and Wolman, 1960). Lateral erosion occurs when stream flow imparts sufficient stress on the outside bank of a meander bend to detach material from the bank (Nanson and Croke, 1992). As erosion of the outer bend occurs (see Figure 2), lateral accretion of material on the inside of channel bends often occurs simultaneously (e.g. Nanson and Hickin, 1986). Lateral channel migration is thus dependent on the flow conditions within the channel and the ability of the bank to resist erosion by stream flow (Nanson and Croke, 1992).

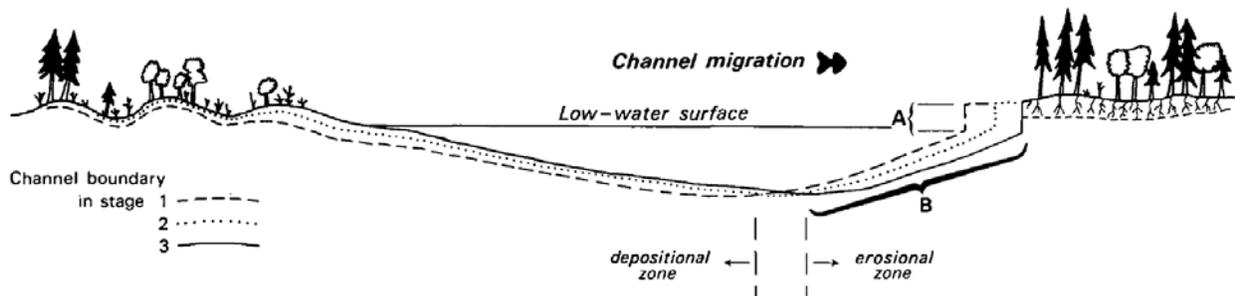


Figure 2. A migrating channel in cross-sectional view. A schematic diagram by Nanson and Hickin (1986) showing a cross-sectional view of a channel at a migrating meander bend. Shifts in the channel through time are indicated by the channel boundary stages and are reflected by the vegetation age progression shown on the depositional (left) side of the channel.

Bend migration is governed by the balance between erosive forces imparted by flowing water and the resisting forces of stream banks and floodplain materials. Total stream power is the rate of energy expenditure along a stream and is commonly expressed as the product of discharge and channel slope (Yang, 1973). The rate at which channels migrate laterally generally increases with stream power, therefore, larger channels tend to migrate at greater rates (e.g. Nanson and Hickin, 1986; Richard et al., 2005). Within a given reach, slope is generally constant and the channel tends to migrate the greatest distances during major flood events (Konrad, 2012). However, all channels experiencing floods do not necessarily migrate, since channel migration is also heavily dependent on the resistance of the material comprising the bank (Nanson and Croke, 1992). Flows must exceed the threshold needed to mobilize or erode the bank material. Factors that increase bank resistance include sediment size and cohesion. Cohesion is either from chemical bonds associated with clay particles or mechanical from plant roots (Thorne, 1990). Riparian vegetation can increase cohesion several orders of magnitude and thus have a significant effect on bank erosion (Langendoen et al., 2009).

The balance between sediment transport capacity and sediment supply also has a large influence on a channel's tendency to migrate (Dunne et al., 2010; Harrison et al., 2011; O'Connor et al., 2014). A channel's stream power determines the quantity and size of sediment it is able to transport, which is referred to as the sediment transport capacity (Knighton, 1998). If the amount of sediment supplied to a channel reach exceeds the transport capacity, sediment deposition

occurs. Because flow velocity is slowest on the inside of meander bends, gravel bars are preferentially formed at the inside of meander bends (Knighton, 1998). Bars on the inside of bends divert stream flow toward the outer banks of meander bends, causing bank erosion and gradual bend migration.

Because of the greater tendency for channel migration with sediment deposition, local reductions in sediment transport capacity often correspond to channels with relatively large migration rates (Dunne and Dietrich, 1979; Dunne et al., 2010). Variations in longitudinal profiles (gradients) of streams are often controlled by variation in bedrock geology. At channel reaches where gradients abruptly reduce, sediment deposition and channel migration are common (Montgomery and Buffington, 1997). In cases where slope reductions are extreme and valleys widen abruptly, landforms called alluvial fans can form (Summerfield, 1991) (further discussed below).

Channel avulsions

Abrupt switches in channel course, called channel avulsions, are a common form of channel migration (Leopold et al., 1995). Avulsions range in frequency and size from relatively regular avulsions, that cut new channels across meander bends (meander cutoffs), to infrequent valley-scale avulsions (Figure 3). The type and frequency of avulsions depend on rates of bend migration, floodplain slope, riparian vegetation (Constantine et al., 2009), the presence and transport of large wood (Fetherston et al., 1995; Abbe and Montgomery, 1996; Collins et al., 2012), and a valley's geological history (Slingerland and Smith, 2004).

Meander cutoffs

Meander cutoffs are generally the most common avulsion type, regularly creating new channels between meander bends (Knighton, 1998). Meander cutoffs accompany bend migration – as bend migration lengthens channels, meander cutoffs reduce the length of channels (Constantine and Dunne, 2008). Therefore, the frequency of meander cutoffs is in part dictated by the rate of gradual migration at bends. Individual meander cutoffs impact floodplain areas according to the size of the channel and meander bend size (Leopold and Wolman, 1960) (Figure 3). Individual meander cutoffs on large rivers can therefore affect large areas of the floodplain. Meander cutoff avulsions commonly occur every few years or decades at multiple bends along a river and collectively create floodplain landforms such as oxbow lakes, side channels, and swales that provide aquatic habitat and floodplain complexity (Ward and Stanford, 1995; Abbe and Montgomery, 1996; Beechie and Bolton, 1999; Latterell et al., 2006; Dunne et al., 2010; Collins et al., 2012).

Meander cutoffs are classified as either neck or chute cutoffs (Knighton, 1998) (Figure 3). Neck cutoffs occur when migrating channel bends impinge upon adjacent downstream bends, forming a new channel. Neck cutoffs therefore involve almost strictly lateral erosion of the floodplain surface, which contrasts with chute cutoffs (Figure 3). A chute cutoff involves erosion of a new channel across a meander bend. Chute cutoffs form when overbank flows during floods erode downward into the floodplain surface between meander bends. Chute cutoffs can occur when channel obstructions (e.g. logjams) divert flow over banks, but can also occur in the absence of channel obstructions (Constantine et al., 2009). Floodplain slope and vegetation coverage control whether overbank flows can erode chutes into the floodplain surface. In particular, dense

vegetation slows down overbank flows and resists erosion of the floodplain surface, and floodplain slope corresponds with the erosive power (stream power) of overbank flows. As a result, floodplains with relatively steep and sparsely vegetated floodplain surfaces are more prone to chute cutoffs. Where the combination of gentle floodplain slope and dense vegetation completely prevents chute cutoffs, bend migration will progress until neck cutoff occurs.

Island-forming avulsions

Island-forming avulsions (Figure 3) occur as channels switch around “hard-points” in the floodplain formed by stable log jams (Fetherston et al., 1995; Abbe and Montgomery, 1996; Montgomery and Abbe, 2006; Collins et al., 2012). These hard-points capture and accumulate sediment supplied by overbank floods (Abbe and Montgomery, 1996). Repeated sediment deposition on hard-points causes them to rise in elevation through time and then persist with stands of living mature and old-growth forests (Latterell et al., 2006). Mature and old-growth forests growing on hard-points become important sources for large woody debris to channels (Latterell and Naiman, 2007). Diversion points of island-forming avulsions typically coincide with stable logjams (Montgomery and Abbe, 2006). Island-forming avulsions are a key process in anabranching channels, which are discussed in detail below. Logjam-induced channel changes can occur in channels ranging from less than 0.01% (e.g., channels in estuarine and deltaic environments) to mountainous valleys (Abbe and Montgomery, 2003).

Valley-scale avulsions

Individual avulsions that impact areas along large portions of valleys are generally infrequent, with recurrence intervals typically greater than hundreds of years (Slingerland and Smith, 2004). These large-scale avulsions differ from the types of avulsions already discussed in that they are not part of typical channel migration processes, but are instead a result of long-term erosion and/or sediment deposition. Large-scale avulsions generally are considered to result from long-term deposition by a river channel (Bryant et al., 1995). Long-term deposition causes river channels to build landforms called “alluvial ridges” and become elevated relative to adjacent areas of the floodplain. Valley-scale avulsions may occur when floodplain gradients between the river channel (perched atop the alluvial ridge) and adjacent low-lying areas are sufficient for overbank flows to erode a new channel.

In the Puget Sound region, rivers that have deposited sediment since the most recent continental glaciations, which ended approximately 14,000 years before present (Booth and Hallet, 1993), often sit on top of alluvial ridges which suggest a potential for valley-scale avulsions (Collins and Montgomery, 2011). While not observed since widespread European settlement, a large-scale avulsion occurred within the past thousand years in the Nooksack River valley (Pittman and Maudlin, 2003).

Glacial braided rivers like the White and Carbon Rivers draining Mt. Rainier can have convex valley cross-sections where the active river channel is situated above surrounding floodplain areas, setting up conditions for major avulsions. These situations are often exacerbated by historic levee confinement which causes rivers to aggrade above surrounding floodplain areas (Czuba et al., 2010). Levees reduce the natural tendency of migrating channels to equilibrate landforms and to moderate the magnitude of avulsions. In general, long-term control of rivers such as historic levees can set up more serious risks over time.

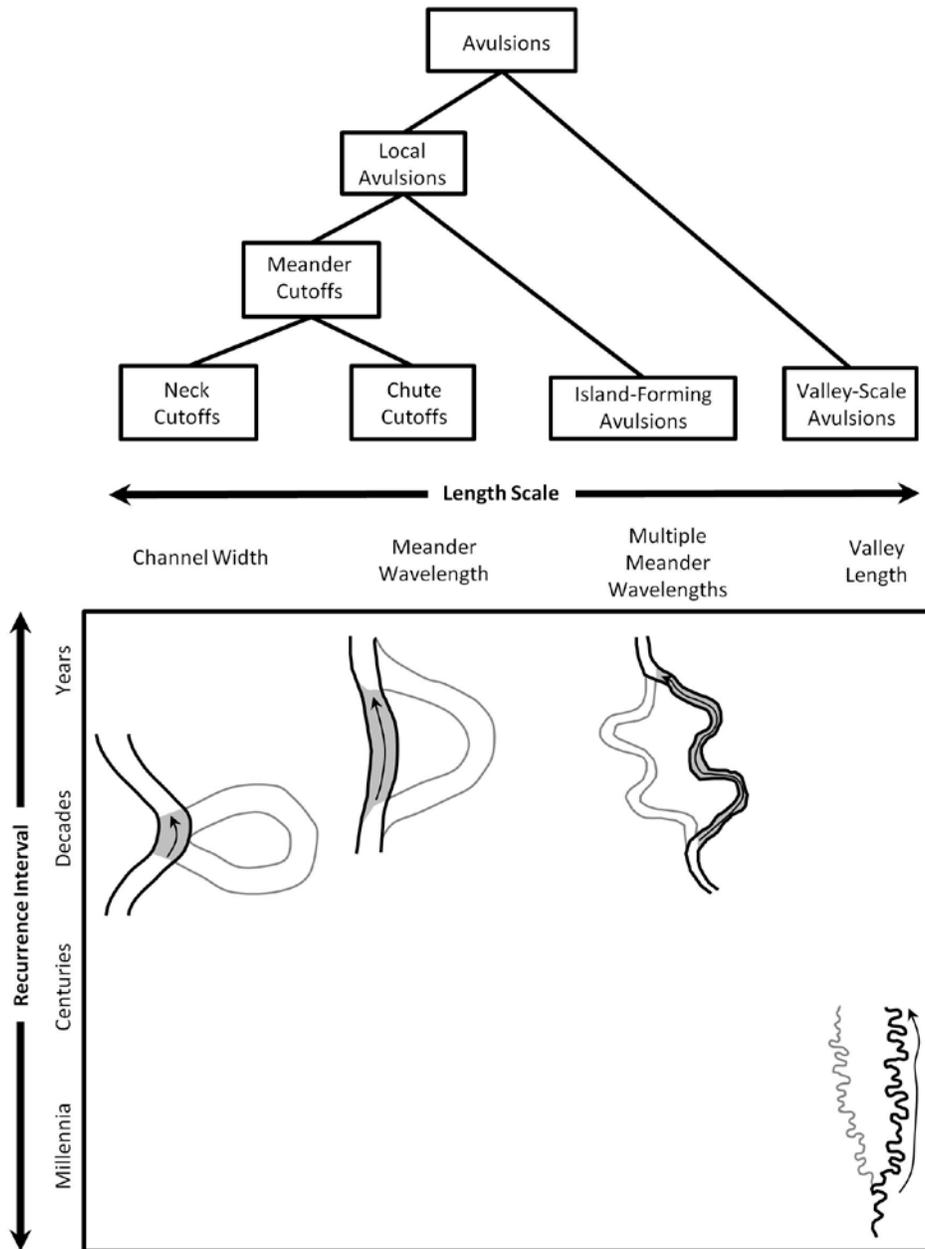


Figure 3. Classification of channel avulsions. A hierarchical classification of avulsions of the active channel plotted by approximate length-scale and recurrence interval. The relevant length is that of the channel formed by an avulsion (shaded grey). Active, post-avulsion channels (black) and inactive channels abandoned at the time of avulsion (grey outlines) illustrate the style and length-scale of each avulsion type. Local and valley-scale avulsions define the most basic division (Slingerland and Smith, 2004). Meander cutoffs, a form of local avulsions, are relatively regular occurrences in actively migrating streams, and are classified as neck and chute cutoffs. Island-forming avulsions are defined here as avulsions that occur around forested islands in floodplains dominated by old-growth forests that generate large logjams (Montgomery and Abbe, 2006).

Alluvial fans

Relatively steep confined channels that enter a larger, lower- gradient valley will form an alluvial fan. Alluvial fans form from multiple avulsions through time (Summerfield, 1991). Abrupt reductions in channel gradient common on alluvial fans trigger bed aggradation that can raise the channel bed above the surrounding terrain and cause an avulsion which sends the channel to another part of the fan. Alluvial fans by definition are CMZs and considered high hazard zones for any type of land-use.

Riparian vegetation and large wood

Because wood entering a stream can influence flow hydraulics, bank erosion, channel grade, and channel migration processes, patterns of forest cover also influence channel form (e.g. Swanson et al., 1978; Sedell and Froggatt, 1984; Gurnell and Petts, 2002; Abbe and Montgomery, 1996; Collins et al., 2002). When in-stream wood adds roughness to a channel bed it reduces the stream's ability to transport sediment, which reduces the median grain size of the bed material (Manga and Kirchner, 2000). Fallen trees can also deflect flow at channel banks and trigger local bank erosion. Large wood and floodplain forests, however, can reduce the rate of bank erosion and channel migration. In the large rivers of the Olympic Peninsula (Washington) and the Sacramento River (California), channel migration rates in floodplain areas with mature forests are approximately half of those in floodplain areas with non-existent or immature forests (Abbe et al., 2003; Micheli et al., 2004). These examples illustrate the ability of mature forests to stabilize channels and reduce channel migration rates.

Large wood in channels often causes side and secondary channels to form, which in turn provide productive aquatic habitat (Sedell et al., 1990; Gregory et al., 1991; Gurnell et al., 2002). Side and secondary channels diverge from and reconnect to the main channel and often convey stream flow during low-flow conditions. Logjams are often found at the heads of perennial side channels, acting to divert flow into the channel (Collins et al., 2002, 2003; Montgomery and Abbe, 2006; Sear et al., 2010). Logjams also regulate the amount of flow supplied from the main to side channel and stabilize the heads of side channels to prevent avulsion (Collins et al., 2003; Abbe and Montgomery, 1996). Side channels often occupy sloughs, oxbow lakes, and other topographic depressions created by migration of the main channel (Collins et al., 2002).

Channel migration induced by channel incision

Confined streams can also be subject to channel incision and migration if there is a change in geomorphic controls (Booth et al., 2004). For example, many lowland streams flow through small valleys draining intensively developed uplands. These streams typically experienced significant downward erosion, or incision, in response to historic clearing of riparian forests and in-stream wood that previously had checked the channel's grade. Compounding this situation, runoff from development increased peak flows and in turn the stream's erosive energy (Konrad and Booth, 2002). As channels cut down, flows that once spread out onto heavily vegetated floodplains are now confined to a smooth deep channel, further accelerating incision (Simon, 1989). Incision destabilizes stream banks and in steep ravines can destabilize entire hillslopes. Incision also threatens buried pipelines, bridge abutments, and road embankments. Once the

channel reaches an equilibrium grade, sediment begins to accumulate in the channel and channel widening begins (Simon, 1989). Reaches downstream of those experiencing incision will experience elevated inputs of bedload (gravel-sized) sediment which can accelerate lateral migration.

These examples underscore why understanding the processes of vertical and lateral erosion, and the factors controlling channel resilience (e.g., vegetation and wood), is critical to understanding channel migration. The discussion also is intended to emphasize the fact that channel migration is not solely limited to large rivers or the simple lateral migration of a channel meander. Rather, channel migration can occur throughout a channel network and be influenced by a range of geomorphic processes.

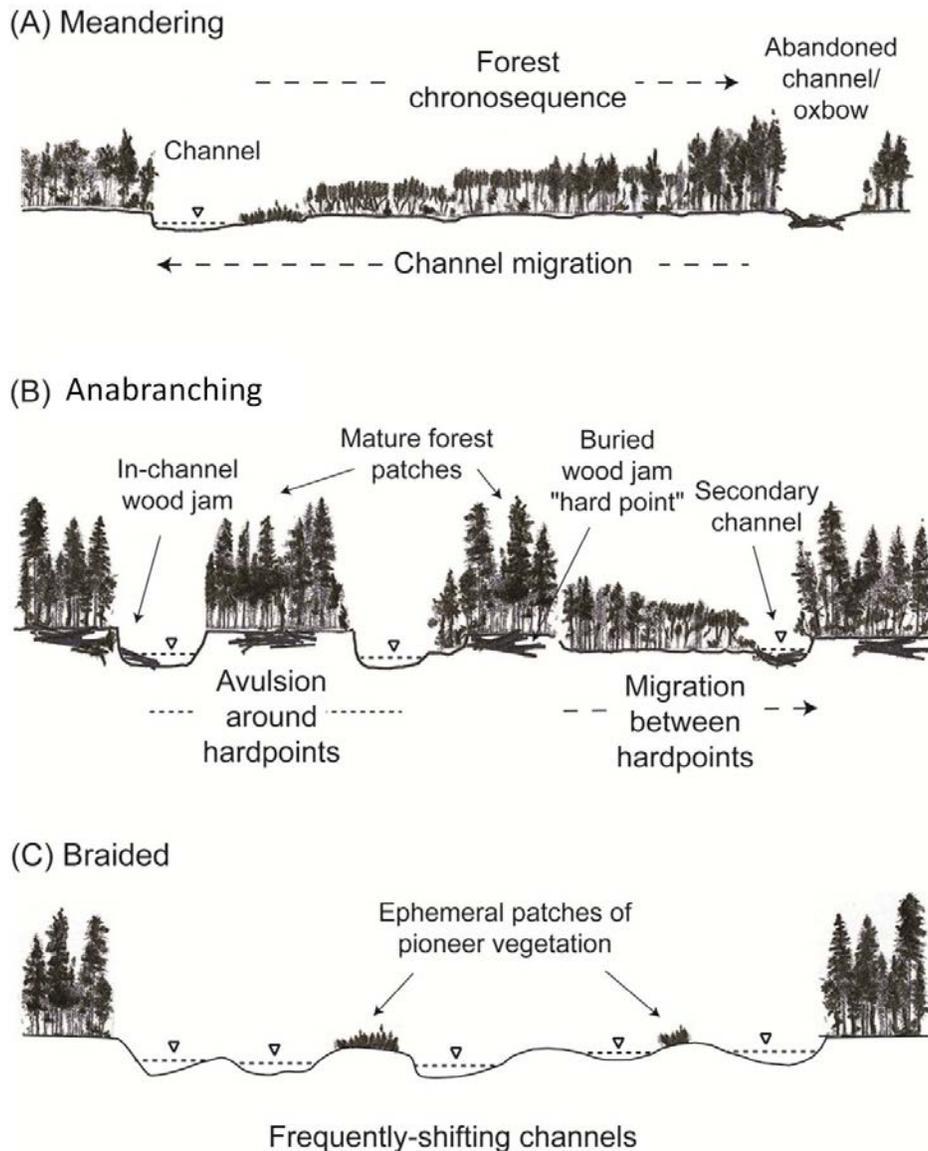


Figure 4. Cross-sectional views of channel patterns in Western Washington. Key features of each pattern are labeled. Triangles indicate low-flow water surfaces. The diagram is reproduced with permission from Collins et al. (2012).

Channel Patterns in Western Washington

Channel patterns in unconfined valleys of Western Washington can be classified as meandering, anabranching, and braided (see Figures 4 and 5) (Beechie et al., 2006). However, while channel pattern classification may be useful for communication, it should be recognized that channel patterns lie on a continuum on which the boundaries between patterns are fuzzy (Leopold and Wolman, 1957). The purpose here is to highlight the common channel migration processes, characteristics of, and landscape controls on each channel pattern. The discussion supports a general conceptual model of channel patterns and channel migration for Western Washington discussed in the last section of this chapter.

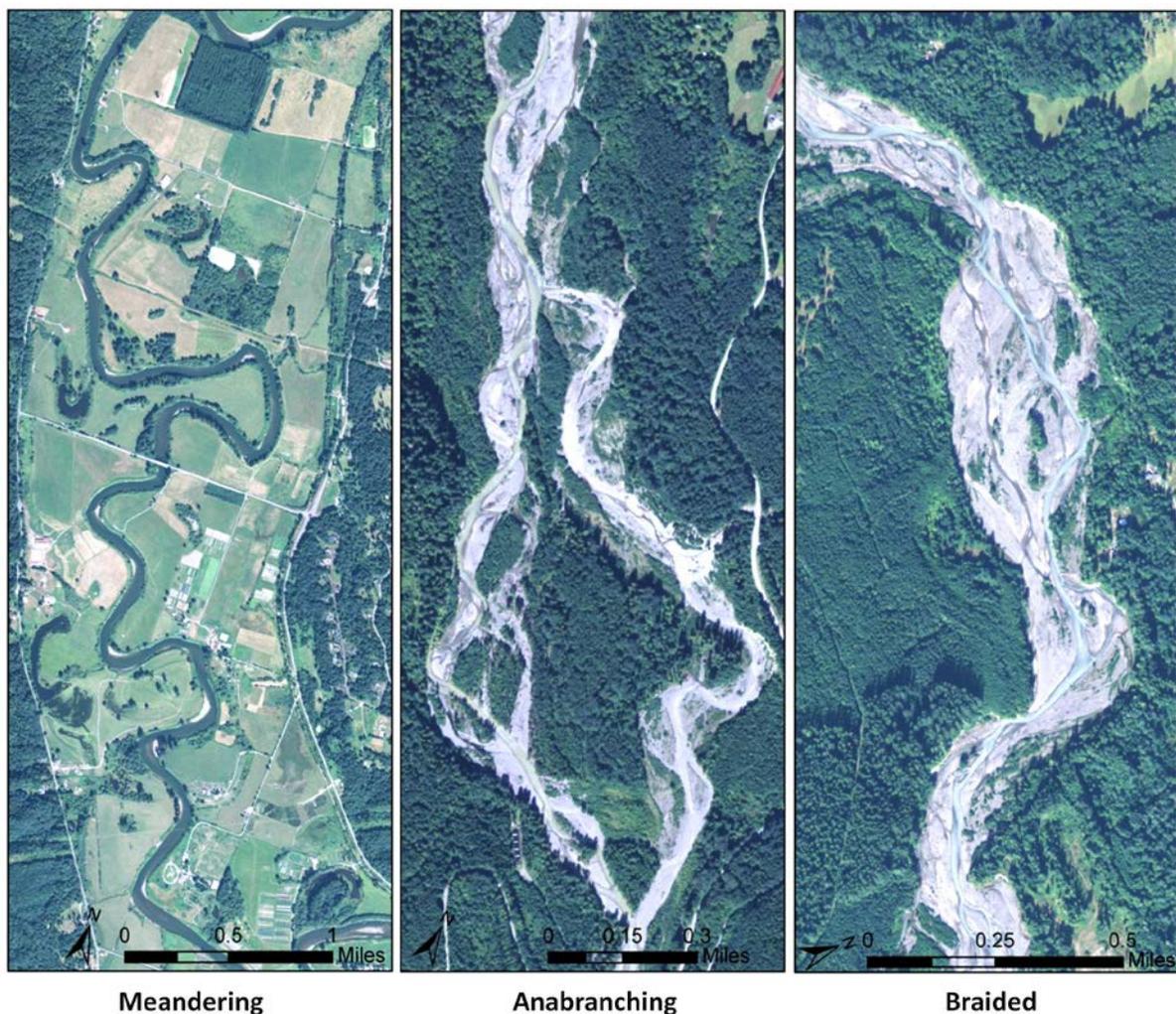


Figure 5. Aerial views of channel patterns in Western Washington. Aerial images of the meandering, anabranching, and braided channel patterns of the Snoqualmie, Middle Fork of the Nooksack, and Nisqually Rivers, respectively, taken by the National Aerial Imagery Program in 2011.

Meandering channel pattern

Meandering channels are single-threaded, sinuous channels that migrate through a combination of gradual bend migration and meander cutoffs (Leopold and Wolman, 1957). Floodplain topography is characterized by mosaic of meander scrolls and abandoned channels, oxbow lakes, and swales resulting from meander cutoffs. Meander scrolls are subtle, arc-shaped ridges and valleys formed on the inside of meander bends as they migrate outward (Leopold et al., 1995) (Figure 6). In these floodplains, forest ages are dictated by channel migration rates (Hickin and Nanson, 1975; Hickin, 1984). Forest stands often increase in age with distance from the channel on the inside of meander bends, reflecting gradual migration of bends (Figure 4).

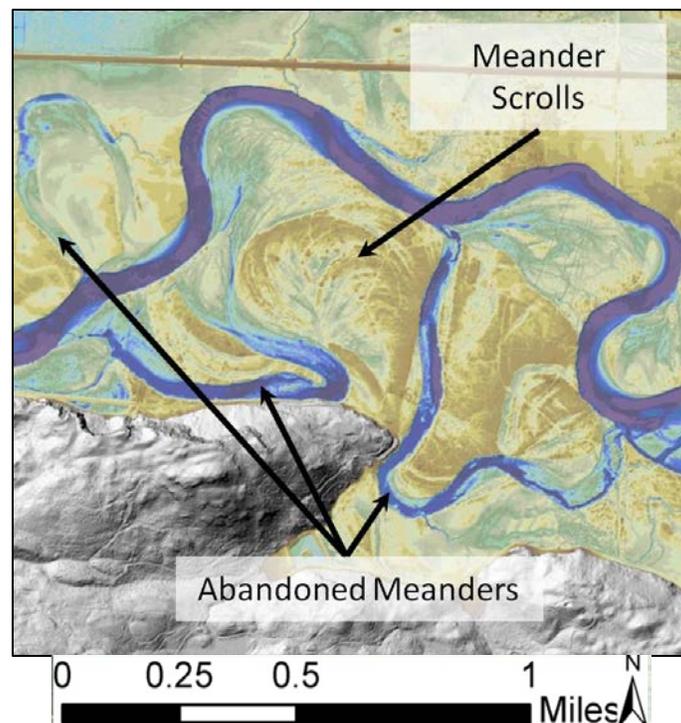


Figure 6. Landforms of a meandering stream. A high-resolution topographic map of the Cowlitz River (Lewis County, WA) floodplain, which is an example of floodplain topography and landforms created by a meandering stream. Multiple abandoned meanders and meander scrolls are visible. The map is colored by relative elevation to the active channel, with cool colors at low elevations relative to the river, and warm colors at high elevations (maximum of 25 feet) relative to the river.

A measure used to describe the form of meandering channels is sinuosity, or the ratio of channel length to valley length (Leopold et al., 1995). A sinuosity value of one corresponds with a straight channel relative to its valley. Channel sinuosity is related to the predominant type of meander cutoffs occurring within a channel (Constantine and Dunne, 2008). In particular, channels with a greater tendency towards chute cutoffs generally have a smaller sinuosity, whereas channels dominated by neck cutoffs tend to be more sinuous (Constantine and Dunne, 2008). As discussed above, relatively steep and sparsely vegetated floodplains tend toward chute cutoffs, and therefore they are expected to be less sinuous relative to floodplains with predominantly neck cutoffs (Constantine et al., 2009).

Measurements by Collins and Montgomery (2011) of Puget Sound rivers prior to widespread-European settlement reveal a negative relationship between valley slope and sinuosity, suggesting that these rivers respond to controls found in other regions (Figure 7). In many river systems of Western Washington, channels have since straightened in response to clearing of floodplain forests and human manipulation of river channels.

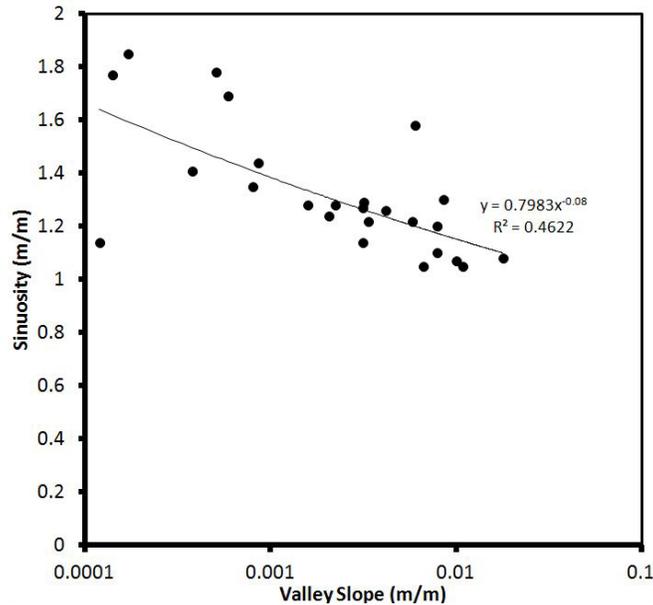


Figure 7. Sinuosity of Puget Sound rivers. valley slope (rise/run) versus sinuosity for major rivers and streams draining to the Puget Sound. Data from Collins and Montgomery (2011).

Anabranching channel pattern

Anabranching channel patterns have multiple active channels divided by stable, forested islands during low and high flows (Figures 4 and 5) (Nanson and Knighton, 1996; Abbe and Montgomery, 2003). In forested regions, large wood is a dominant control in forming and maintaining anabranching channels (Abbe and Montgomery, 1996; Montgomery and Abbe, 2006; Collins et al., 2012). In Western Washington and other forested regions, anabranching channels have been referred to as anastomosing (Knighton and Nanson, 1993; Collins et al., 2003, 2012), island braided (Ward et al., 2002; Beechie et al., 2006), and wandering (Desloges and Church, 1989; Gottesfeld and Johnson Gottesfeld, 1990). However, these terms are not necessarily interchangeable in all cases. For example, one type of anastomosing channel (generally rare in Washington) is characterized by fine sediment (sand-size and smaller) in the bed and banks, low gradients, and cohesive banks, and is less influenced by large wood (Knighton, 1998). Conversely, the anabranching channels discussed from this point forth have moderate gradients and significant gravel content on their beds and in their banks (Nanson and Knighton, 1996; Beechie et al., 2006), which commonly leads to exposed gravel bars during low flows.

Anabranching channels have multiple channels at low flows and bankfull flows. Vegetated islands are visible even during floods. Each channel thread typically has a low width-to-depth

ratio. These characteristics contrast with braided channels (discussed below), which have bars that only are visible during low flows. During a bankfull or greater flow, the bars are submerged and a braided channel becomes one channel (Figure 4). Braided channels also have large width-to-depth ratios (Knighton, 1998).

In forested areas, mature riparian forests and large woody debris are integral components in the formation of anabranching channels (Abbe and Montgomery, 1996; Fetherston et al., 1995; Abbe and Montgomery, 2003; Collins et al., 2003, 2012; Montgomery and Abbe, 2006). Stable hard-points formed around log jams create flow obstructions which deflect and split flow (Montgomery and Abbe, 2006). Logjams reduce the radius of curvature of channel meanders, which in turn can raise water elevations and trigger avulsions (Abbe and Montgomery, 2003). Stable logjams form when wood carried in the channel racks and stabilizes around a stable key piece formed by a large log (Abbe and Montgomery, 1996, 2003; Collins et al., 2002). Large logs serving as the key piece typically are at least 100-200 years old, depending on the species (Collins et al., 2012). Sediment deposition behind logjams creates surfaces for new forest to establish (Abbe and Montgomery, 1996).

Buried logjams protect these forest patches growing on alluvial surfaces from erosion and channel migration, allowing them to mature (Abbe and Montgomery, 1996; Abbe and Brooks, 2011; Collins et al., 2012). Through time, sediment is deposited on the stable patch, raising its elevation above the surrounding floodplain (Montgomery and Abbe, 2006). With multiple elevated hard-points, floodplain surfaces have a patch-work topography, which contrasts with the meander-scroll topography of floodplains with meandering channels (Figure 6). Island-forming avulsions occur around stable hard-points, and gradual channel migration and meander cutoffs occur between hard- points (Figure 4). The dynamics of wood recruitment, logjam and hard-point formation, and channel migration in anabranching channels are summarized in Figure 8.

Because the anabranching channel pattern depends on the presence and supply of large wood capable of forming logjams, it is sensitive to logging of mature and old-growth floodplain forests (Abbe et al., 1997; Collins et al., 2002, 2012). Such logging may transform anabranching channels into either meandering or braided channels. (Abbe et al., 1997; Collins et al., 2003, 2012). Widespread logging and channel wood removal during the early and middle 20th century resulted in decreased numbers of forested islands, increased channel width, and fewer side channels, all of which are associated with reductions in the quantity and quality of aquatic habitat (Abbe et al., 1997, 2003; Wohl, 2011). Depending on the dominant species and growth rates of floodplain forests, anabranching channels may take 50 to 300 years to recover as mature forests reestablish (Collins et al., 2012). However, engineered logjams represent one possible intervention that may accelerate recovery (Abbe et al., 1997; Abbe and Brooks, 2011).

In general, wood creates a more complex channel and floodplain mosaic, but it also introduces stability. Removal of wood and mature riparian forests generally increases channel migration rates and allows the historic channel migration zone to expand (Brooks and Brierley, 2002; Abbe et al., 2003).

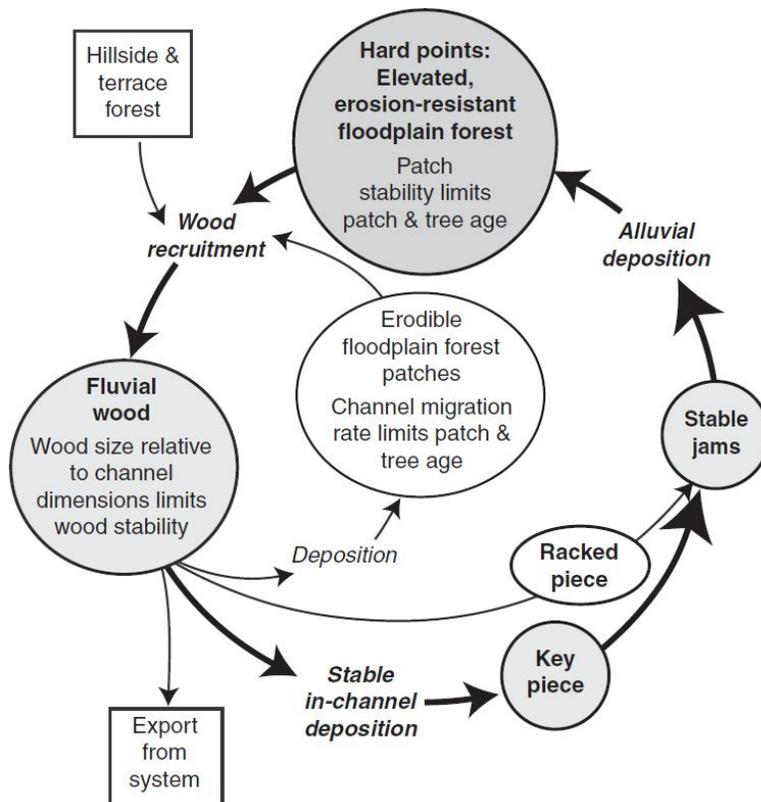


Figure 8. The floodplain-large wood cycle. A flow chart showing the floodplain-large wood cycle in forested valleys. Reproduced with permission from Collins et al. (2012).

Braided channel pattern

Braided channels have multiple channels separated by exposed sediment bars or islands with young, ephemeral vegetation (Leopold and Wolman, 1957) (Figures 4 and 5). Braided channels often have erodible banks and are often found on steep floodplains that have a large supply of coarse sediment (Knighton, 1998). The combination of high sediment supply and steep channels results in frequent small-scale avulsions around bars. Braided streams are often considered the least stable channel pattern due to their frequent bar formation, channel thread switching, and the rapid migration of the wetted channel (Leopold and Wolman, 1957). The small-scale avulsions around bars shift the thalweg of the channel frequently, sometimes over the course of days. The term “thalweg” refers to the line connecting the deepest points along a channel (Summerfield, 1991). Oftentimes, thalweg shifting occurs within the active channel – the low-flow channel plus exposed bars inundated during high flows (Wood-Smith and Buffington, 1996)– and does not erode vegetated floodplain surfaces. Further, braided channels generally lack woody vegetation and their banks are more susceptible to erosion. During high flows, bars are submerged and the channel becomes single-threaded, and migration of the active channel is more likely.

Linking channel migration processes with patterns

Geomorphologists are often captivated by process-form linkages, meaning they seek to understand the underlying set of landscape processes that create particular landforms. This paper focuses on unique combinations of channel migration processes (e.g. bend migration, different avulsion types) that create and sustain particular channel patterns on floodplains. Channel patterns reflect the unique suite of channel migration processes occurring with a channel reach. Figure 9 demonstrates this point clearly by showing the unique combinations of avulsion types that distinguish each pattern.

Realizing these process-form linkages can be especially important for floodplain restoration projects, where projects often seek to create or restore particular physical features which offer beneficial aquatic habitat. In these scenarios, restoration scientists will often have the greatest chance to achieve habitat improvement goals over the long-term when they attempt to restore the physical processes that will sustain the desired landforms and channel pattern into the future (Beechie et al., 2010).

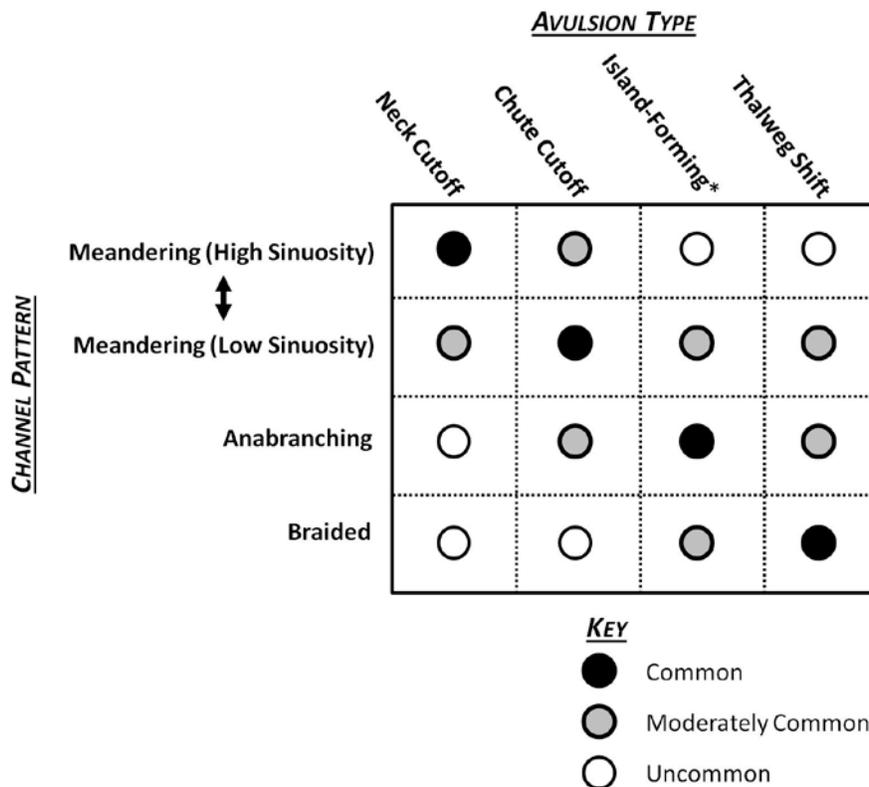


Figure 9. Channel pattern versus predominant avulsion types. The matrix shows unique combinations of different avulsion types occurring within channels of each pattern. Meandering channels are divided into low and high sinuosity types to show the range in avulsion types within. The asterisk indicates that large wood is assumed present so that island-forming avulsions are possible. Thalweg shift describes small-scale avulsions around gravel bars within the active channel (Schumm, 1985).

Matrix of channel patterns in Western Washington

The conceptual matrix shown in Figure 10 plots the three major channel patterns (meandering, anabranching, and braided) in Western Washington on common axes and essentially summarizes concepts of channel migration processes and channel pattern discussed in this document. The conceptual matrix relates landscape controls grouped as “Erosion Potential” and “Influence of Large Wood” to channel pattern and process. Erosion Potential is classified qualitatively based on factors of floodplain slope, sediment supply, and sediment transport capacity, which were discussed as controls on channel migration in previous sections. Each factor lists a series of categorized landscape classifications ordered according to the over-arching axis. The Influence of Large Wood axis is classified in terms of abundance and age of wood supplied through channels and present on floodplains.

The top axis of the channel pattern matrix (Figure 10) captures general changes in channel migration rate (including avulsion frequency) occurring along with changes in erosion potential. The channel pattern matrix does not account for channel size (e.g. channel width or discharge), which has been found to correlate significantly with channel migration rate (e.g. Nanson and Hickin, 1986; Richard et al., 2005). Therefore, when using the matrix, migration rate should be considered with respect to a channel of a given size.

An important nuance of the channel pattern matrix is that channel migration rate (top axis of Figure 10) refers to the rate of lateral movement of a channel thalweg. Lateral migration rate of the active channel is also important in floodplain management, but it is not captured directly in the matrix. Migration rate of the channel thalweg is generally found to increase with slope and sediment supply (Dunne and Dietrich, 1979; Nanson and Hickin, 1986; Richard et al., 2005; Harrison et al., 2011), but relationships between these variables and migration rate of the active channel are not as clear. In single-threaded meandering channels, migration rates of the thalweg and active channel should correspond closely; however, frequent (sometimes daily) thalweg shifts within the active channel of braided channels are often accompanied with little movement of the active channel, meaning the rate of thalweg shift should significantly exceed migration rate of the active channel.

The right axis of the channel pattern matrix (Figure 10) shows general changes in channel form (number of side channels and forested islands) occurring with increasing influence from large wood. As discussed in the section on anabranching channels (above), forested islands formed around large, erosion-resistant logjams are key features of the anabranching channel pattern. Therefore, increasing influence from large wood can increase the frequency and/or area of forested islands (Abbe and Montgomery, 1996, 2003; Gurnell and Petts, 2002; Fetherston et al., 1995; O’Connor et al., 2003; Montgomery and Abbe, 2006). As discussed above in the section on riparian vegetation and large wood, logjams also commonly are found at the upstream ends of perennial side channels at the divergence point from the main channel. Therefore, increasing abundance of wood is expected to correspond to increases in the length and number of side channels.

While classifying channels is a convenient way to describe a channel’s form, the process domains of each channel pattern lie on a continuum of the controlling landscape variables (Leopold and Wolman, 1957; Eaton et al., 2010). This continuum concept means channels often

are hybrids of, and can vary continuously in space and time between, classified patterns in response to changes in the landscape. For instance, a channel may gradually transition from braided to meandering in response to a gradual reduction in valley slope (Brierley and Hickin, 1991). Alternatively, a channel may transition from meandering to braided during a period with multiple large floods (Konrad et al., 2011).

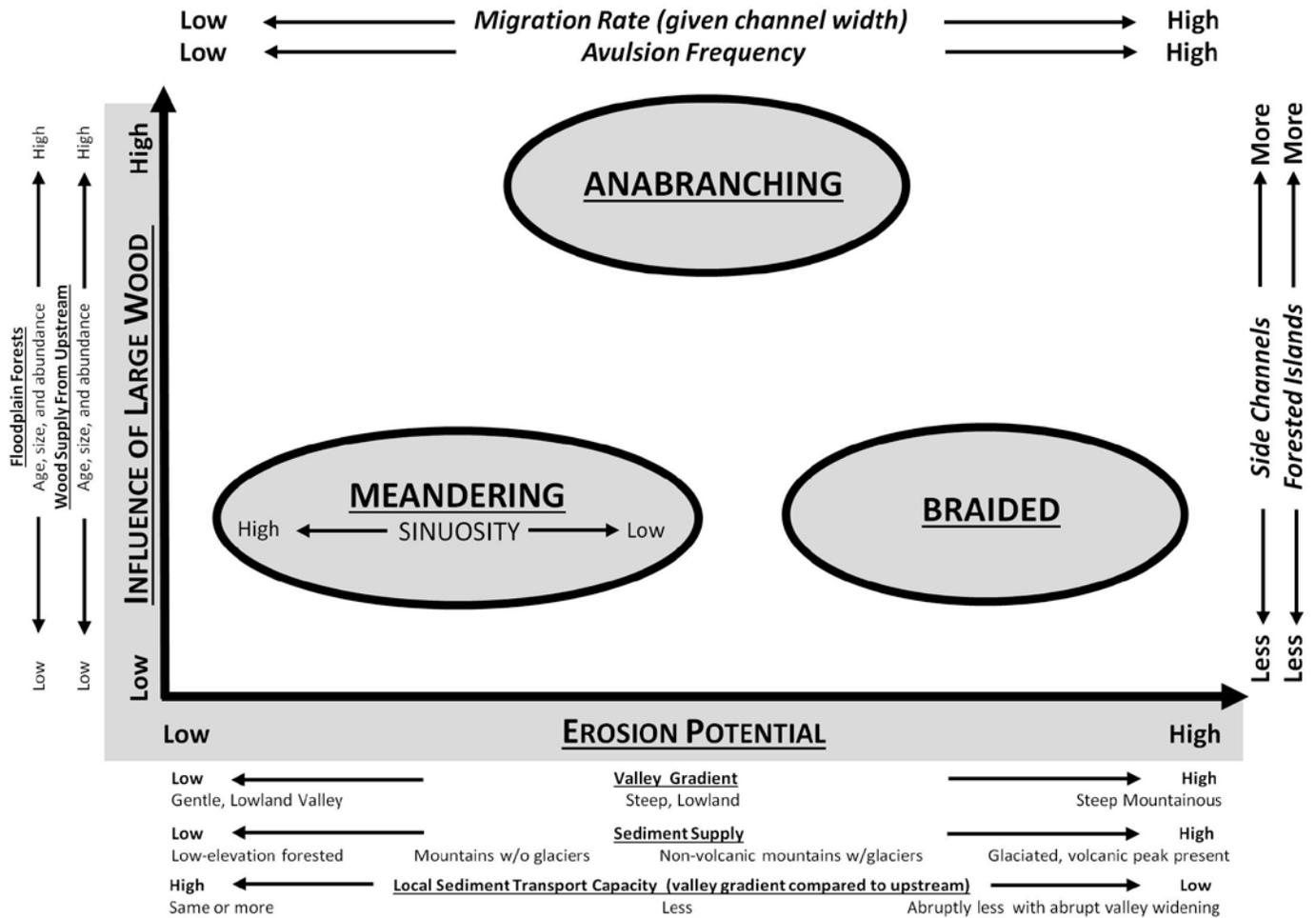


Figure 10. Matrix of channel patterns in Western Washington. A conceptual matrix illustrating landscape controls on channel patterns and channel migration processes in Western Washington. Independent variables that control channel pattern and processes plot along the bottom and left axes. Classified channel patterns are plotted according to the two axes, and general characteristics are shown along the right and top boundary of the matrix. Classification of sediment supply should consider the characteristics of a watershed above the channel reach of interest. Classifying a stream’s “Local Sediment Transport Capacity” requires comparing the gradient of the subject to reaches directly upstream. At locations where the gradient abruptly reduces, localized sediment deposition and enhanced channel migration are expected. These locations may occur where channels emerge from steep and confined bedrock valleys into valleys with lower gradients and wide bottoms. The conceptual reasoning behind the relationships shown is described in-text.

The matrix also displays how a channel may respond through time to changes in land-use. For example, an anabranching channel may transition to a meandering or braided channel in response to floodplain clearing, depending on the valley characteristics (Collins et al., 2002).

Alternatively, a meandering channel with side channels sustained by the presence of logjams may simplify (have decreasing numbers of side channels) in response to forest clearing.

Summary

Streams in Western Washington display a variety of channel patterns reflecting varying suites of channel migration processes operating along unconfined valleys (see Figures 1 and 9). The combination of channel migration processes occurring along a single channel reach results from the characteristics of its watershed and valley bottom (Figure 1). Watershed characteristics control factors like stream discharge, sediment supply, and wood supply which in turn influence channel migration processes and patterns. Valley bottom characteristics such as slope and riparian vegetation abundance dictate a stream's erosion potential.

The three main channel patterns include meandering, anabranching, and braided. Each unique pattern is sustained by a distinct set of channel migrating processes. Meandering channels are single-threaded, sinuous channels that migrate through processes of gradual bend migration and meander cutoffs. The sinuosity of meandering channels reflects the predominant type of meander cutoffs occurring. Anabranching channels have multiple active channels separated by forested islands. Large logjams stabilize forested islands and cause channels to avulse around them. The enclaves of large trees growing on islands in turn provide large logs to channels, causing formation of new islands and thus sustaining the anabranching channel pattern. Braided channels are characterized by multiple channels flowing and frequently shifting around sediment bars. During high flows, bars are submerged and the channel becomes a single thread.

The matrix of channel patterns (Figure 10) conceptually connects landscape controls on channel migration with the three channel patterns. Whereas chapters on *Landscape Context* and *Channel Migration Processes* develop connections between landscape factors and channel migration processes (upper large arrow in Figure 1), and much of the chapter on *Channel Patterns* connects channel migration processes to pattern (lower large arrow in Figure 1), the channel pattern matrix bridges the gap by connecting landscape variables to channel pattern. The matrix therefore draws together many of the concepts in this paper, and also acts as a useful tool.

Concepts outlined in this document are a foundation for thinking about numerous applied problems in floodplain management and restoration. Almost all applied floodplain problems demand strategic thinking in the form of project prioritization, development of hypotheses, and attempts at achieving multiple project benefits. A few example scenarios and questions where this document could be of help in addressing those problems include:

- *In order to improve off-channel salmonid habitat, we want to focus our watershed restoration efforts on river reaches that naturally can sustain side channels. Which river reaches should we prioritize, and what measures are necessary to stimulate geomorphic processes that naturally sustain side channels?*
- *We wish to prioritize the mapping of highly-active channels in our ten-year county-wide channel migration zone mapping initiative. Which channel reaches are likely to be most active and why?*

- *A particular channel reach has seen an uptick in channel migration rates and a series of channel avulsions. What possible conditions may be changing and causing these channel changes?*

In many cases, the reader may use this paper as a starting point to explore more technical information. The Further Reading and Bibliography sections provide many resources.

Further Reading

Textbooks on general fluvial forms and processes

- Knighton, D., 1998, *Fluvial forms and processes: a new perspective*: Arnold, Hodder Headline, PLC.
- Leopold, L.B., Wolman, M.G., and Miller, J.P., 1995, *Fluvial processes in geomorphology*: Courier Dover Publications.

Articles on channel migration and floodplain processes

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Articles on considering channel pattern and migration in floodplain restoration

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