A Framework for Delineating Channel Migration Zones

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Washington State Department of Ecology

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by

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Figure 17 The ES is determined by estimating an erosion rate, dx/dt, for the design life of the CMZ **(a)**, and does not always begin along the active channel, but from the margins of the area that encloses the HMZ and/or the AHZ. The GS is intended to account for a vertical bank composed of erodible material that will adjust to a more stable configuration from mass wasting processes (slumping, landsliding, etc.) **(b)**, even if river erosion ceases (i.e., the channel moves away from the bank).

Figure 18 In this conceptual example, the EHA (ES + GS) includes the areas at risk of erosion based on the design life of the CMZ, trends in channel movement **(1)**, rates of channel migration, bank characteristics, bank erosion associated with AHZs **(2)**, and geologic constraints **(3)**. In this example, the meanders of the channel are generally trending in the downstream direction, and in many cases are currently eroding into the HMZ. The abandoned channels previously highlighted as avulsion hazards (**Figure 10**) will also experience channel migration if the main active channel occupies them. Accordingly, the EHA includes bank erosion occurring from AHZs as well as bank erosion associated with current trends in channel behavior.

Figure 19 The DMA, the final component of CMZ delineation, takes into account the effects of man-made constraints (levees, revetments, railroads, etc.) that prevent channel migration into areas that would otherwise be at risk of erosion (EHAs). In this example, a levee located at **(1)** substantially confines the CMZ, which may result in more instability (accelerated channel migration and erosion) directly downstream **(2)**.

Figure 20 In this conceptual erosion hazard map, the current active channel is highlighted (blue) to illustrate how trends in channel movement make this river susceptible to erosion beyond its HMZ. Consequently, the areas downstream of the migrating channel are highlighted as a severe erosion hazard. Additionally, the AHZ identified as **(1)** is severely at risk in the event of a channel avulsion given its likelihood of occupation, which would be followed by lateral erosion. The other AHZ **(2)** is considered a moderate erosion hazard because it is less likely to be occupied by the main channel.

List of Acronyms

AHZ	Avulsion Hazard Zone
CFCMP	Comprehensive Flood Control Management Plan
CMZ	Channel Migration Zone
DEM	Digital Elevation Model
DMA	Disconnected Migration Area
DOE	Department of Ecology
EHA	Erosion Hazard Area
ES	Erosion Setback
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
GIS	Geographic Information Systems
GLO	General Land Office
GS	Geotechnical Setback
HMZ	Historical Migration Zone
LiDAR	Light Detection and Ranging
LWD	large woody debris
MRCI	Municipal, Residential, Commercial, and Industrial Development and Redevelopment
NRCS	Natural Resources Conservation Service
NFIA	National Flood Insurance Act
NFIP	National Flood Insurance Plan
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RCW	Revised Code of Washington
SMA	Shoreline Management Act
USC&GS	United States Coast and Geodetic Survey
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WAC	Washington Administrative Code

1 Introduction

Flooding stands out as the single most pervasive disaster hazard facing the nation. It causes an estimated $6 billion in property damages annually. In the past, many of the nation's efforts to avert flood disasters have focused on structural changes to waterways—for example, building dams and levees. Focusing flood (reduction efforts on identifying) the areas at risk for flooding and steering development away from those areas can be a less costly long-term approach to mitigation.

—President's Budget of the U.S. Government, Fiscal Year 2003

The geomorphic complexity of such alluvial streams creates difficulties for implementing Federal floodplain regulations that are based primarily on flooding. In fact, channel changes, such as meander migration, and bank erosion, may constitute a greater hazard than overbank flow in some areas.

—Federal Emergency Management Agency 1999

Approximately one-third of the nation's streams experience severe channel erosion; more than half of these events occur in the Northwest and the Southwest (FEMA 1999). Rivers in Washington State are especially prone to unanticipated channel erosion due to the legacy of glaciation and the effects of large woody debris (LWD) on channel bed dynamics. In many instances, outwash terraces are assumed to be "topographic constraints" because they lie well above the 100-year floodplain. However, terraces composed of erodible material (such as glacial outwash or alluvium) can erode more rapidly than floodplain surfaces due to landslides initiated by riverine erosion of the hillslope toe. Additionally, stable log jams initiate aggradation of the channel bed, much like a small dam, thereby causing the channel to flood and erode greater portions of the floodplain. (Fluctuations in LWD loading also contribute to the formation of floodplain surfaces often mistaken as terraces. In fact, these surfaces are made of alluvial materials that are prone to erosion, just as outwash terraces or other floodplain banks).

Common tools used to assess flood hazards, such as Flood Insurance Rate Maps (FIRMs), are based on fixed-bed hydraulics and do not characterize areas susceptible to channel erosion either within or outside of the areas prone to flooding. As a result, many floodplain and floodway boundaries on FIRMs are reliable for only short periods after their production. Given their short-term reliability and focus on inundation, FIRMs fall short in portraying the geomorphic hazards that bank erosion may pose to land and structures. This limits their usefulness in planning areas that are safe for development. As a consequence, the costs of property lost to bank erosion are commonly transferred to the landowner.

The principal goal of delineating the Channel Migration Zone (CMZ)—the area where a stream or river is susceptible to channel erosion—is to predict areas at risk for future channel erosion due to fluvial processes. CMZ delineations help reduce risks to human communities by guiding development in and along river systems away from such areas. Limiting development within CMZs also reduces the costs of repairing or replacing infrastructure and major civil works that might otherwise be threatened or damaged by channel migration. Additionally, CMZ delineations can provide guidance in reducing degradation and loss of critical aquatic and riparian habitats, helping assure that fluvial process are accommodated and that the river landscape is not permanently degraded or disconnected from the river by development.

1.1 Purpose, Limitations of this Report

This report, prepared in light of proposed revisions to Chapter 173-26 WAC (the Shoreline Management Guidelines) and for purposes of flood hazard management, is intended as a guidance document for local governments and practitioners, based on up-to-date, peer-reviewed research[1]. While offering a thorough and systematic procedure for identifying and delineating CMZs, the approach and methods presented in this document:

- represent only **one** approach to CMZ delineation;
- are not mandated for local government use under any state law;
- do not replace existing regulatory definitions of CMZs; and
- are intended to be applied in areas under Shoreline jurisdiction (as defined by the Shoreline Management Act).

Ecology believes this delineation methodology, though an intensive approach, will result in optimum data upon which to make planning and resource management decisions. We are aware that other methodologies exist that are not as resource-intensive; the use of these methods may be appropriate depending on the scale of application (e.g., planning vs. site-specific permitting).

This report provides a basic overview of CMZ and fluvial geomorphic concepts to agency managers and supporting personnel. However, expertise in fluvial geomorphology is essential for correctly identifying fluvial features and interpreting geomorphic processes acting on the river landscape. Key field and analytical personnel must therefore be proficient in fluvial geomorphology (e.g., possess a graduate degree in Geology or Physical Geography with specialization in fluvial geomorphology, and have at least two years of professional experience).

1.2 Regulatory Context

Both state and federal regulations support the use of CMZ delineations. The following laws relate to CMZs and their application to flood regulations and habitat protection. However, it is important to note that use of the CMZ delineation methodology outlined in this document does not assure compliance with these state and federal laws and regulatory requirements.

National Flood Insurance Act of 1968

Both federal and state regulations support the use of CMZ delineation for managing flood hazards and protecting floodplain functions. The centerpiece of national policy for managing flood hazards is the National Flood Insurance Act of 1968 (NFIA), which is administered by the Federal Emergency Management Agency (FEMA). The intent of the NFIA is to reduce future flood damage through community floodplain management ordinances and provide protection for property owners against potential losses through the National Flood Insurance Plan (NFIP).

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[1] Ecology acknowledges the approach and methods outlined in this document need to be tested with a case study and updated accordingly.

In Washington State, Washington State Department of Ecology (DOE) is designated to carry out all functions and precepts related to the National Flood Insurance Act. According to Chapter 86 RCW, *Flood Control,* local jurisdictions within the state are required to adopt a Comprehensive Flood Control Management Plan (CFCMP) in order to qualify for funds allocated by DOE for flood control assistance. Each CFCMP is expected to meet the minimum requirements for participating in the NFIP as well as additional requirements adopted by the DOE. Within a CFCMP, local jurisdictions are required to identify and manage their floodplains and channel meander belts. A meander belt may in some instances be similar to a CMZ, although it may not account for avulsion and erosion hazards that are included in a CMZ.

Shoreline Management Act

The Shoreline Management Act (SMA), also administered by DOE, requires local governments with "shorelines" and "shorelines of state-wide significance" to prepare Shoreline Master Programs (SMPs). SMPs are both planning and regulatory documents containing policies and regulations for managing uses and activities within shorelines subject to the SMA: "Applicable shoreline master programs should include provisions to limit development and shoreline modifications that would result in interference with the process of channel migration that may cause significant adverse impacts to property or public improvements and or result in a net loss of ecological functions associated with the rivers and streams" (Chapter 173-26 WAC, 58). As part of a SMP inventory process, the proposed guidelines require local governments to identify the location of CMZs for streams and rivers within their boundaries that are subject to the SMA: "The channel migration zone should be established to identify those areas with a high probability of being subject to channel movement based on historic record, geologic character and evidence of past migration. It should also be recognized that past action is not a perfect indicator 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" (Chapter 173-26 WAC, 58). Likewise, the proposed guidelines acknowledge the need to anticipate future channel change that may not be reflected in the historical record.

The Endangered Species Act

Under Limit 12 of the 4(d) Rule, the Endangered Species Act (ESA) also requires the delineation of CMZs in order to determine how habitat functions are affected by proposed development in areas of Municipal, Residential, Commercial, and Industrial Development and Redevelopment (MRCI). The 4(d) Rule is one of the means by which a local government may ensure that activities they authorize are both legally permissible under the ESA and consistent with the conservation of threatened species. For example, in Washington State, several species of salmon, steelhead, and bull trout are listed as endangered or threatened under the ESA. National Oceanic and Atmospheric Administration (NOAA) Fisheries (formerly called the National Marine Fisheries Service) administers the ESA for conservation of anadromous fish (salmon and steelhead); the U.S. Fish and Wildlife Service (USFWS) administers the ESA for conservation of bull trout and other aquatic and terrestrial species. Both these agencies evaluate whether MRCI development ordinances or plans adequately conserve listed fish under their jurisdiction. Within their twelve evaluation considerations, NOAA Fisheries and USFWS consider impacts to riparian buffer zones, which are measured from the edge of the CMZ. They also consider how MRCI development ordinances or plans will safeguard CMZs and avoid bank hardening. In both cases, a CMZ must first be delineated in order to establish where a riparian buffer begins, or to evaluate a proposed action within a CMZ.

1.3 Summary of CMZ Delineation Process

CMZ studies analyze historical information and field data to interpret past and current channel conditions in order to predict future channel behavior and areas at risk of channel movement. Delineation of a CMZ relies on an evaluation of channel processes that occur within a multi-dimensional context (space and time). Channels respond with horizontal movement (lateral migration, avulsion, channel widening, cannel narrowing) and vertical movement (incision and aggradation) depending on site-specific circumstances and watershed conditions. Thus, patterns and rates of channel movement must be estimated by using a combination of historical and field studies to determine future trends in channel migration (bank erosion and avulsion). The CMZ study takes into account trends in channel movement, context of disturbance history and changes in boundary conditions, as well as topography, bank erodibility, hydrology, sediment supply and woody debris loading.

The CMZ boundary delineates the area in which channel processes will occur over a specified period of time. Consequently, the timeline used for a CMZ delineation will affect the relative area included in the CMZ. For example, a CMZ intended to capture channel processes for 100 years into the future may be smaller in area than a CMZ intended to capture channel processes for 500 years. The boundary of the CMZ is stationary for the design life of the CMZ delineation; it does not change unless channel erosion hazards are not properly accounted for in the original CMZ delineation, leading to unanticipated erosion.

When delineating CMZs, it is helpful to view the river landscape as a series of identifiable components (**Figure 1**) that can be used collectively to define the boundaries of the CMZ:

1. The *Historical Migration Z*one (HMZ)—the collective area the channel occupied in the historical record (**Section 4.1**).
2. The *Avulsion Hazard Zone* (AHZ)—the area not included in the HMZ that is at risk of avulsion over the timeline of the CMZ (**Section 4.2**).
3. The *Erosion Hazard Area* (EHA)—the area not included in the HMZ or the AHZ that is at risk of bank erosion from stream flow or mass wasting over the timeline of the CMZ. The EHA has two components: the Erosion Setback (ES) and the Geotechnical Setback (GS). The ES is the area at risk of future bank erosion by stream flow; the GS is defined by channel and terrace banks that are at risk of mass wasting (due to erosion of the toe). The GS projects from the ES at a side slope angle that forms a stable bank configuration, thereby accounting for mass wasting processes that will promote a stable angle of repose (**Section 4.3**).

4. The *Disconnected Migration Area* (DMA)—the portion of the CMZ where man-made structures physically eliminate channel migration (**Section 4.4**).

Accordingly, delineation of the CMZ (**Figure 1**) is the cumulative product of historical analysis and field interpretations, characterized by the following equation:

$$CMZ = HMZ + AHZ + EHA - DMA$$

$$(EHA = ES + GS)$$

Field studies are used in combination with historical studies to define the AHZ, EHA and DMA by field mapping and assessment of surficial geology, fluvial landforms, geotechnical characteristics and current physical conditions of the given area. When applied to historical data analysis, field observations (on-the-ground data) provide the means for interpreting future channel change and delineating the boundaries of the CMZ. Accordingly, the AHZ, EHA, and DMA may not apply in every CMZ study. However, in river systems susceptible to avulsion and/or erosion beyond the HMZ, accounting for these components by limiting development in geologically and geomorphically hazardous areas reduces risk.

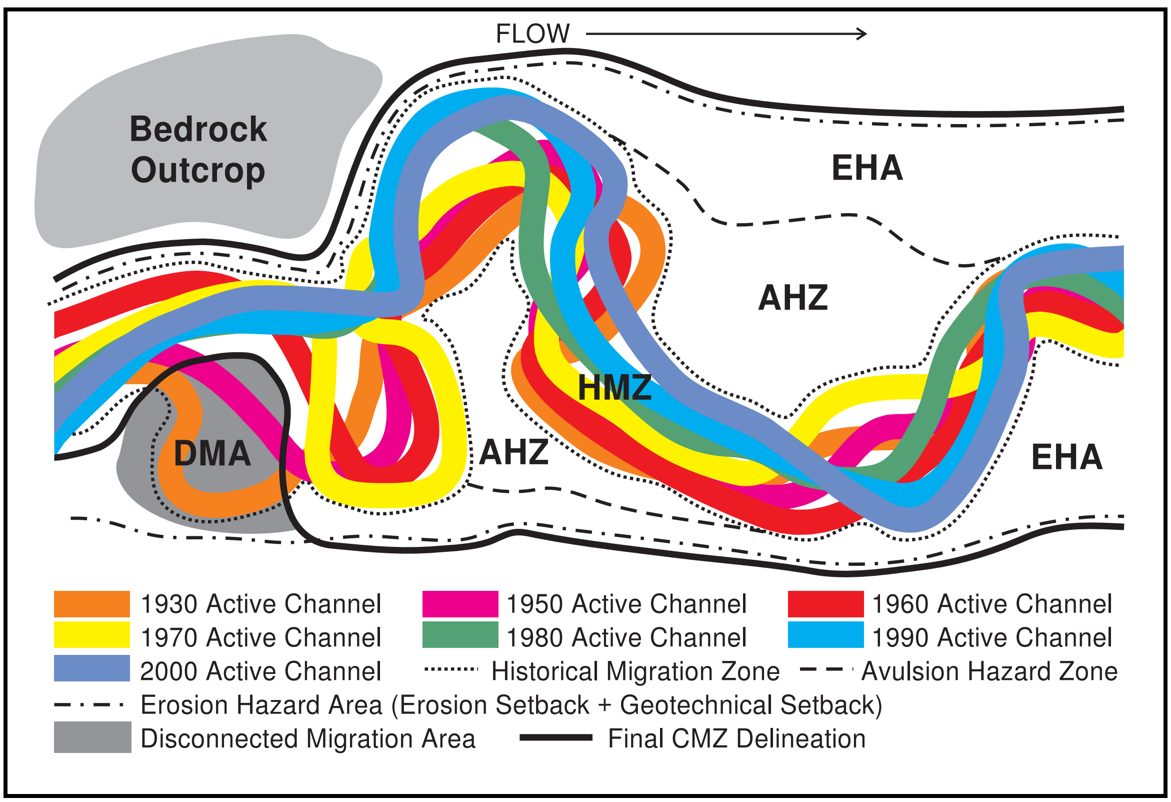

Figure 1. An example of the CMZ as the cumulative product of the Historical Migration Zone (HMZ), the Avulsion Hazard Zone (AHZ), the Erosion Hazard Area (EHA), and the Disconnected Migration Area (DMA) based on historical and field analysis and interpretation.

2 Description of Common Terms

CMZs typically encompass floodplains and some portions of terraces. Although CMZs may simply correspond to the channel itself, as is the case with bedrock canyons, CMZs can also extend from hillslope to hillslope across the entire valley bottom, as is the case with some alluvial rivers. Following are descriptions of the basic features found within and outside CMZs.

Channel Networks

The drainage system of channels that convey surface water, subsurface flow, sediment, and organic matter (**Figure 2**) are referred to as the *channel network*. How these inputs move through the channel network depends on the physical characteristics of the stream reach relative to the magnitude of inputs introduced to the system (Montgomery and Buffington 1993 and 1998). A channel network is divided into source, transport, and response segments based on their sediment supply and transport capacity. *Source segments* deliver sediment to the channel network primarily through colluvial (hillslope) processes; *transport segments* convey sediment downstream; *response segments* accumulate sediment in response to changes in sediment supply, discharge, and LWD. Channel reaches (lengths of river that exhibit similarities in confinement, gradient, sediment characteristics and morphology) are classified as *supply-limited* and *transport-limited*. Supply-limited reaches have enough sediment transport capacity to convey all the sediment delivered to them and therefore have little or no sediment storage, such as a bedrock channel.

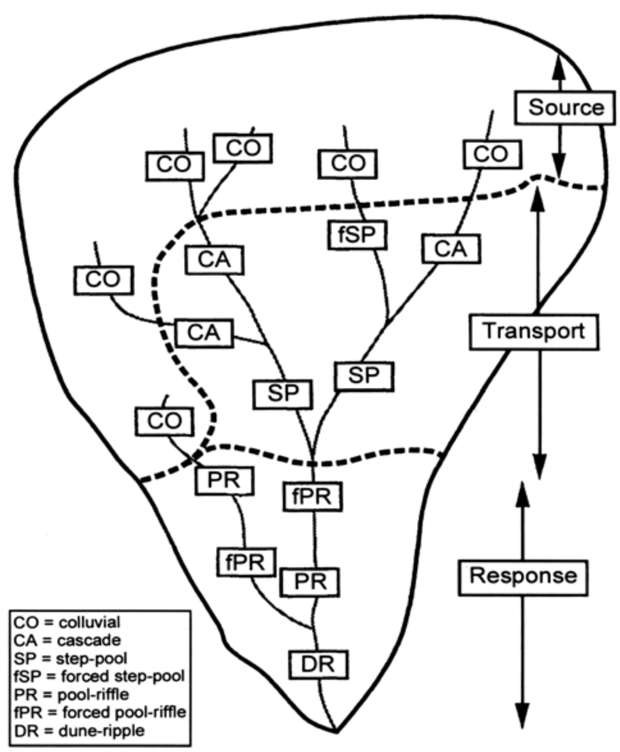

Figure 2. The spatial distribution of reach types within a drainage basin influences the distribution of potential impacts and responses to disturbance (Montgomery and Buffington 1998).

In mountainous terrain, source segments are headwater channels that act as transport-limited sediment storage sites subject to intermittent debris-flow scour. Source segments are steep channels (gradients typically greater than 20%) that episodically deliver sediment to the channel network. Transport segments (typically 4–20% gradient) are supply-limited reaches (bedrock, cascade, and step-pool) that temporarily store sediment, but tend to convey sediment inputs downstream. The majority of channel adjustment occurs in lower-gradient (i.e., less than 3%) response segments because they are moderately confined or unconfined systems that are transport-limited. Transport-limited reaches lack the capacity to move all the sediment that is delivered to the reach and therefore have some sediment deposition within the reach. CMZs typically occur in response segments and transport-limited reaches within the channel network.

Within the channel network, *forced morphologies* can occur where local sediment storage is enhanced in supply-limited channels. Local flow obstructions, such as bedrock outcrops, culverts, bridges, ice jams, and log jams, can create morphologies typical of response reaches by effectively reducing channel gradient and redistributing energy loss throughout the reach. Woody debris and log jams obstruct flow and decrease a channel's capacity to transport sediment, thereby forcing pool-riffle formation in a transport reach with an otherwise plane-bed or bedrock morphology. Woody debris may also force step-pool morphologies in reaches that would otherwise be cascade or bedrock (e.g., Montgomery et al. 1996). It is important to recognize forced morphologies because (1) they can occur almost anywhere in the channel network; (2) understanding the type of obstructions that can govern bed morphology and where they occur is important for anticipating how channels may change over time, particularly in regards to changes in flow regime, riparian conditions, and watershed land use; (3) they commonly occur throughout Washington State; and (4) they affect CMZ delineation by raising the elevation of the stream bed, thereby accessing wider portions of the valley bottom.

Channels

Channels are pathways through which water, sediment, and organic debris are conveyed through a watershed (**Figure 3**). Channels are formed and maintained by flowing water and can be vegetated or unvegetated. Channels that actively convey sediment commonly have evidence of recent sediment deposition or bed scour, as well as sediment that is in temporary storage (e.g., bars).

Channels are commonly described by their flow characteristics (perennial, intermittent, ephemeral) and sediment transport (alluvial, non-alluvial) characteristics. *Perennial* channels convey water year-round; most large streams in humid regions are perennial. *Intermittent* channels only flow during certain times during the year when they receive water from springs or runoff; during dry years, intermittent channels may cease to flow entirely or may be reduced to a series of separate pools. *Ephemeral* channels are event-driven and convey water during or immediately after rain. Most of the streams in desert and semi-arid regions are intermittent or ephemeral; some of these channels are dry for years at a time, but are subject to flash flooding during high-intensity storms. *Alluvial* channels adjust their position, dimensions, shape, and gradient according to the actions of the hydrologic regime, level of sediment supply, and other boundary influences, such as the presence of vegetation and woody debris. Alluvial channels include meandering, braided, and anastomosing rivers and streams. A bedrock canyon or colluvial reach are examples of *non-alluvial* channels (Gordon et al. 1992).

Active channels are "the portion of a channel that is largely unvegetated, at least for some portion of the year, and inundated at times of high discharge" (Montgomery and MacDonald 2002, 1:7). Active channels are usually unvegetated because their beds are frequently disturbed by flows capable of initiating sediment transport. Frequent scouring of the channel bed discourages colonization by plants. If a river or stream has more than one channel, the *mainstem* channel is the term used to define the largest active channel that conveys the greatest discharge. Smaller active channels are referred to as *side*, *secondary,* or *floodplain* channels. The *thalweg* corresponds to the flow path that follows the lowest elevation within a channel cross-section.

Bankfull stage is defined as the stream level along an alluvial channel that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold 1978). Rivers and streams often have several channels that convey flow at bankfull stage. Because the channel experiences frequent disturbance below bankfull stage (thus the formation and reformation of bars, bends and meanders), the bankfull channel typically lacks well-established, older vegetation. Above bankfull stage, the channel's sediment transport capacity decreases and is typically dominated by overbank deposition. The bankfull channel is rarely static and fluctuates over time as the channel bed aggrades and incises. Notably, previous attempts have been made to define the bankfull channel by the 1.5-year flood discharge. Because the bankfull channel reflects on-going geomorphic processes, rivers do not have a common recurrence interval or bankfull stage (Williams 1978). Therefore, geomorphic characteristics, not flow recurrence, are used for defining bankfull stage.

Relic channels are abandoned channels (not presently active). Relic channels can be mapped using substrate (presence of bed material consistent with the active or historical system) and topographic characteristics (bank curvature and presence of swales). *Swales* are vegetated ephemeral channels that may or may not correspond to relic channels.

See **Appendix A** for more information on channel patterns and channel movement.

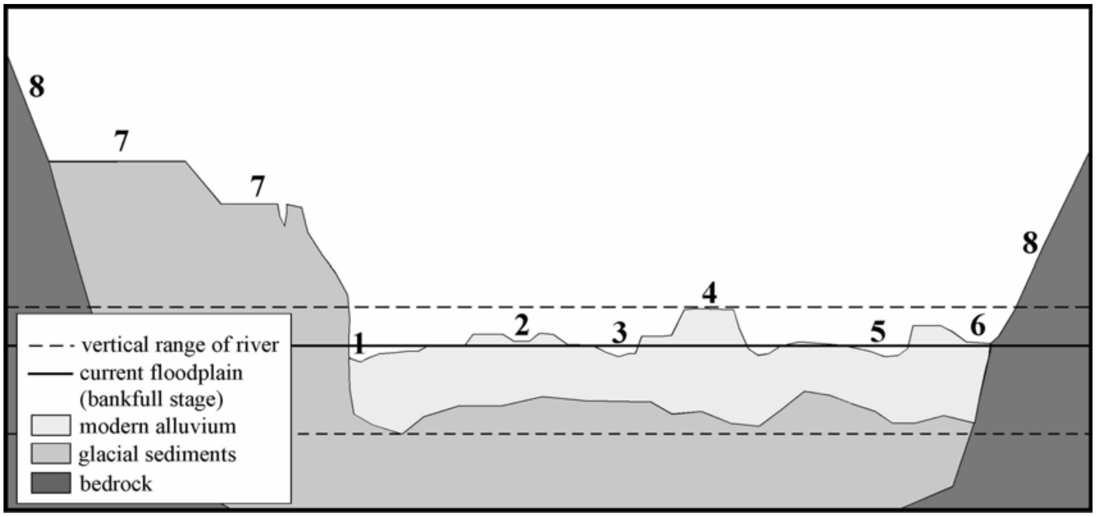

Figure 3. Some of the landforms that are found in an alluvial river valley are illustrated in this cross-section. The active channel (which can be ephemeral, intermittent, or perennial) occurs within the valley bottom and may expand the width of the valley bottom by eroding into adjacent hillslopes **(1)**. Secondary channels can be situated above **(2)** or below **(3)** the active floodplain, and can be either ephemeral or perennial. In some river systems, particularly in heavily forested valleys, the elevation of the active floodplain can rise and lower as the river channel aggrades and incises, thus creating a mosaic of floodplain alluvial surfaces **(4, 6)** that should not be confused with terraces **(7)**. Secondary and abandoned channels can be reoccupied by avulsion **(5)**. Elevated floodplain surfaces with sediments similar to those found in the active channel represent the range of vertical fluctuation in the system under current climatic and vegetative conditions. Terraces composed of material other than modern alluvium represent different climatic and/or geologic conditions and are typically situated well above the modern river valley **(7)**, however these terraces can be susceptible to river erosion **(1)**. Many valleys are set within bedrock **(8)**, but valley walls can also be composed of glacial sediments, as are much of the Puget Sound lowlands.

Floodplains

Floodplains are alluvial depositional features formed by a combination of in-channel and overbank deposits that have been constructed under current climatic conditions. Their evolution is controlled by the rate of sediment supply (volume and size distribution), the availability of sites suitable for accumulation of sediments (valley gradient and confinement), and the stream power of the channel (which determines the volume and size of material that can be transported). A change in one or more of these variables may alter the dominant mode of floodplain construction. For example, an increase in fine sediment supply may cause the channel to switch from in-channel sedimentation to overbank deposition (the dominant process in a low-energy system). During floods, a strong interaction exists between the deep, fast flow of the channel and the shallow, slow-flow of the floodplain; a transfer of momentum occurs from the channel to the floodplain as velocity and shear stress decrease in the channel and increase in the floodplain. This transfer of momentum is accompanied by a flux of suspended sediment (typically silts, clays, sands, and woody debris) from the channel to the floodplain (Knighton 1998).

In terms of floodplain construction, Wolman and Leopold (1957) concluded that lateral accretion and in-channel deposition are the dominant processes of floodplain formation as they account for up to 90% of floodplain materials. If overbank deposition was the main process, then the channel would appear to become depressed within its own alluvium; vertical growth of the floodplain would eventually take it beyond the reach of all but the most infrequent events. Since the relative contributions of lateral and vertical accretion are not constant, overbank deposition becomes more significant where flooding occurs more frequently, where fine-grained material is more readily available, and where channels have greater lateral stability (Brackenridge 1988, Knighton 1998). For instance, when discharge exceeds channel capacity, there is a dramatic increase in the cross-sectional area associated with expansion onto the floodplain. The velocity and depth of water flowing outside of the channel declines rapidly with distance away from the channel. The decline in depth and velocity produces a rapid loss in stream power and competence, which in turn causes coarser particles to deposit near the channel's edge and finer sediment to deposit away from the channel on the floodplain. Multiple occurrences of these floods result in the formation of a berm, or naturally formed levee, that is adjacent to the active channel; as the berm, or levee, increases in height, the capacity of the channel increases, which allows the channel to contain larger discharges (Mount, 1995).

The *meander belt* refers to the historical width of the strip of floodplain previously occupied by the channel where bends have migrated laterally and downstream (Thorne, 1998). The meander belt is not used as a CMZ delineation tool in this report because meander belts themselves migrate; also, channels can avulse and form new meander belts separate from their previous ones. In other words, meander belts are frequently not inclusive of the channel processes that can occur over the design life of the CMZ.

Terraces

An *alluvial terrace* is an abandoned floodplain, produced by past vertical instability in the fluvial system (**Figure 3**). Alluvial terraces are inactive depositional surfaces within the current hydrologic, climatic, and tectonic setting; they can result from a lowering of the river's base level, channel incision, or changes in hydrology. Alluvial terraces give the valley cross-section a stepped appearance. Active floodplain surfaces are sometimes mistaken for alluvial terraces because they may appear to exceed the elevation of flood inundation—an error that may occur more frequently in forested regions, given the influence of large woody debris (LWD) on channel bed dynamics. If a channel abuts the bank of an alluvial terrace, the terrace is at risk of channel erosion, even if it is not subject to flood inundation. In contrast, *strath terraces* are non-alluvial features that are composed of bedrock formed by steady uplift over time. Strath terraces are resistant to erosion, and unlike alluvial terraces, pose a barrier to channel migration.

3 Division of Study Area Into Reaches

The study area is divided into a series of channel reaches that reflect changes in channel pattern, dominant types of channel movement, channel bed morphology, and confinement. These factors are dependent on a wide range of variables and how they interact with one another, including, but not limited to: flow regime (discharge), geologic context, valley morphology, sediment characteristics, sediment supply, riparian vegetation, and woody debris.

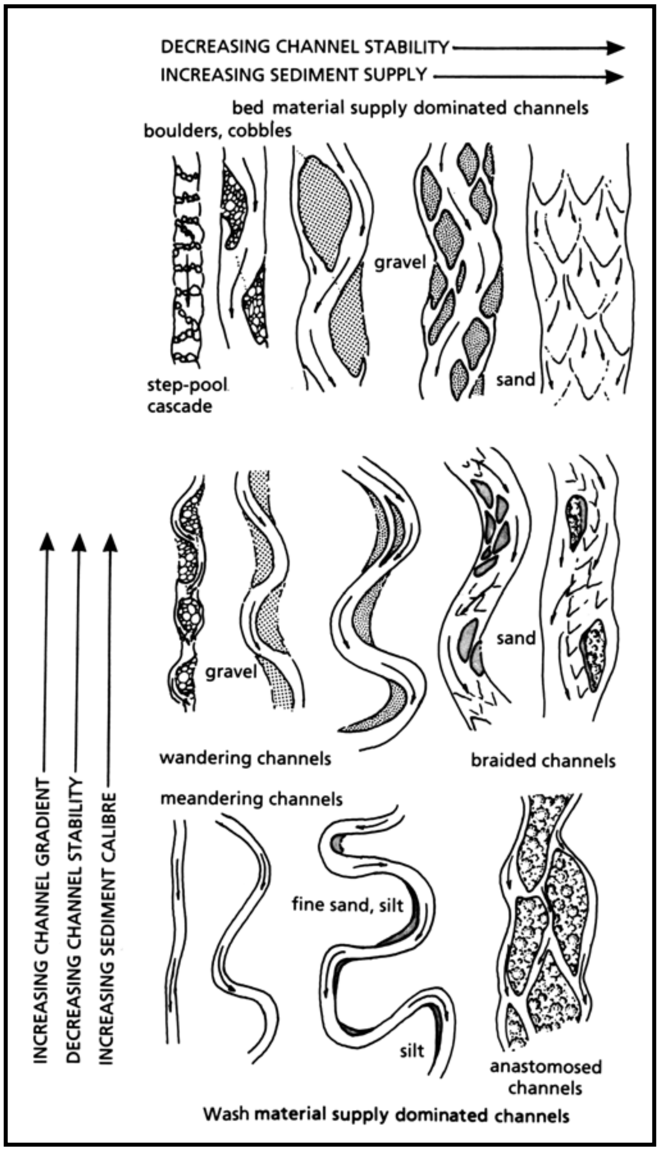

Figure 4. Conceptual pattern of morphological types of large channels (Church 1992). Anastomosed channels tend to be more stable than highly sinuous channels (thus the presence of vegetation between channels and not bars), which is the opposite of what is depicted here.

Channel patterns—braided, meandering, anastomosing, bedrock, and distributary (see **Appendix A**)—are closely related to the amount and character of their available sediment and transport capacity (**Figure 4**), and, in some areas, to the influence of vegetation (Leopold et al. 1995). Changes in channel patterns are indicative of changes in channel processes. For example, a downstream change in channel pattern from meandering to braided may reflect an extreme increase in sediment supply (Smith and Smith 1984). In another example, downstream channel narrowing with an increase in stable, vegetated bars can indicate either a decrease in sediment supply or a decrease in discharge (Patten 1998). Dredging and historical removal of wood from the Stilliguamish River was associated with a change in channel pattern from a complex anastomosing system to a single thread channel (Collins and Montgomery, 2001). Additionally, a change in channel type or sinuosity in sequential aerial photographs can indicate a significant change in discharge, sediment supply, transport capacity, riparian vegetation, or supply of woody debris. Accordingly, changes in channel pattern must be interpreted in the context of these complementary and potentially competing channel processes (Montgomery and MacDonald 2002).

Channel movement describes the change in channel form that occurs from a lateral adjustment of channel banks (lateral migration, avulsion, channel widening, channel narrowing) and/or a vertical adjustment of the channel bed (aggradation, incision). Researchers in fluvial geomorphology have noted that alluvial channels in diverse environments, destabilized by different natural and human-induced disturbances, pass through a consistent, predictable sequence of channel forms over time (e.g., Davis 1902, Simon and Hupp 1986, Darby and Simon 1999). These systematic temporal adjustments are collectively termed *channel evolution* and allow the analyst to interpret past and present channel processes as well as predict future channel changes.

Simon and Hupp (1986) developed a conceptual model for illustrating the changes that occur in incised channel evolution (**Figure 5**), which begins with the equilibrium channel in the initial, predisturbed condition (Stage 1). In Simon and Hupp's model, equilibrium is disrupted through stream channelization (Stage 2) and rapid channel degradation (incision) of the channel bed as the channel begins to adjust (Stage 3). Degradation flattens channel gradient and reduces stream power over time. Concurrently, fluvial undercutting causes the channel banks to become steeper in angle as they increase in height, so that subsequent bank failures occur at the base of the bank. Thus, the degradation (Stage 3) is directly related to destabilization of the channel banks, which leads to channel widening by mass wasting processes (Stage 4), once bank heights and angles exceed the shear strength of the bank material. As incision migrates upstream, aggradation (Stage 5) ensues in previously degraded downstream sites because the flatter gradient at the degraded site cannot transport the increased sediment loads originating from upstream. This secondary aggradation occurs at rates approximately 60% less than the associated incision rate (Simon 1992), consequently the channel bed does not recover to its pre-incision elevation. Attainment of a new dynamic equilibrium (Stage 6) will therefore take place through: (a) bank widening and the subsequent flattening of bank slopes; (b) establishment of riparian vegetation which adds roughness elements, enhances bank accretion, and reduces stream power, and (c) gradient reduction by extending and elongating the meander bend.

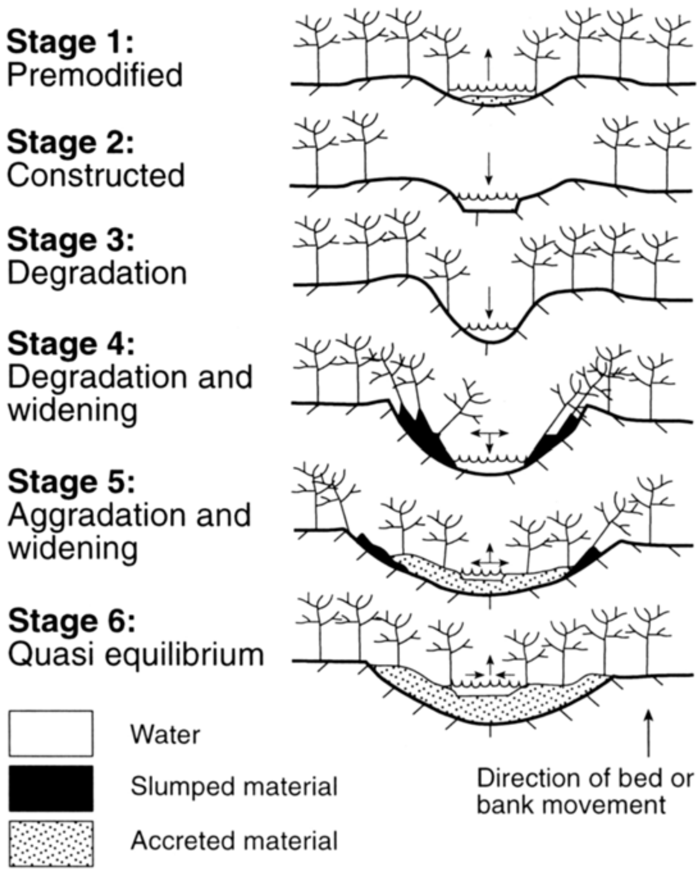

Figure 5. Channel evolution model by Simon and Hupp (1986), which illustrates the dynamic relationship between vertical channel change (incision and secondary aggradation) on horizontal channel movement (channel widening).

Choosing appropriate mitigation and planning measures to reduce future impacts of channel erosion relies on correctly identifying and interpreting a stream's stage of channel evolution and its dominant adjustment processes. Once the dominant processes have been identified, empirical and numerical methods are available to quantify changes in channel form during different stages of channel evolution. Likewise, these techniques can be used to provide estimates of future channel configurations (e.g., Simon and Hupp 1992, Simon and Downs 1995, Darby and Thorne 1996a).

For more information on channel patterns and channel movement, refer to **Appendix A**.

Alluvial channel morphologies—dune-ripple, pool-riffle, plane-bed, step-pool, and cascade—refer to the similar bedforms found over stretches of alluvial stream reaches that are many channel widths in length (10 to 20 channel widths). Alluvial channel morphologies exhibit a wide variety of morphologies and roughness configurations that vary with slope and position within the channel network, and may be confined with little to no associated floodplain, or unconfined with a well established floodplain. For more detail on different types of channel morphologies see Montgomery and Buffington (1997).

Channel confinement refers to the width of the channel's valley walls relative to the width of the bankfull channel; it is a measure for how much a channel can potentially shift within its valley bottom. Based on Montgomery and Buffington (1993, 1997), the Washington Forest Practices Board (1997) links channel confinement and gradient with typical channel bed morphology (**Table 1**) as a basis for delineating channel reaches. Channel confinement falls into three categories: confined, moderately confined, and unconfined. Confined channels have valley bottom widths less than two bankfull channel widths; moderately confined channels have valley bottom widths between two and four bankfull channel widths; and unconfined channels have valley bottom widths greater than four bankfull channel widths. CMZs occur in unconfined and moderately unconfined channels with channel gradients typically between zero and 4%, although CMZs may occur above that (for example, alluvial fans vary in gradient from 3 to 20%).

Table 1. Channel process matrix; VW=valley width, CW=channel width (modified from WFPB 1997). Note that gradients vary between 3 and 20% for alluvial fans (HEC 1993).

Valley Gradient (%) and Typical Channel Bed Morphology		**Degree of Confinement**		
		VW > 4CW Unconfined	**2CW < VW < 4CW Moderately Confined**	**VW < 2CW Confined**
Response	**< 1.0 Pool-Riffle**	Fine Sediment Deposition Bank Erosion Wood Loss (high) Wood Recruitment (high)	Fine Sediment Deposition Bank Erosion Wood Loss (high) Wood Recruitment (high)	…………….
Response	**1.0 – 2.0 Pool-Riffle, Plane-Bed**	Wood Loss (moderate) Wood Recruitment (moderate) Fine Sediment Deposition Bank Erosion	Wood Loss (moderate) Wood Recruitment (moderate) Fine Sediment Deposition Coarse Sediment Deposition Bank Erosion	CMZ = VW
Response	**2.0 – 4.0 Plane-Bed, Forced Pool-Riffle**	Dam-break Flood Debris Flow Deposition Localized Bank Erosion Coarse Sediment Deposition Wood Loss (moderate) Wood Recruitment (low)	Dam-break Flood Debris Flow Deposition Localized Bank Erosion Coarse Sediment Deposition Wood Loss (moderate) Wood Recruitment (low)	CMZ = VW
Transport	**4.0 – 8.0 Step-Pool**	Debris Flow Scour/Deposition Dam-break Flood Wood Loss (low) Wood Recruitment (low)	Debris Flow Scour/Deposition Dam-break Flood Wood Loss (low) Wood Recruitment (low)	CMZ = VW
Transport	**8.0 – 20.0 Cascade**	Debris Flow Scour Wood Loss (negligible) Wood Recruitment (negligible)	Debris Flow Scour Wood Loss (negligible) Wood Recruitment (negligible)	CMZ = VW
Source	**> 20.0 Colluvial**	……………………………...	NO CMZ	NO CMZ

Maps (USGS 7.5' topographic maps) and remote sensing data (aerial photographs, DEM, LiDAR) allow the analyst to initially determine channel reach breaks by confinement, gradient, and channel pattern.

4 Delineating the Channel Migration Zone

Historical studies are important for measuring rates of channel processes by assessing past channel behavior. In combination with field studies, they can provide important information for predicting trends in future channel movement. The longer the record for evaluating channel movement the greater the level of accuracy in the report, *provided that river and land management have been constant over time*. In many cases, the most commonly used historical data (aerial photographs dating to the 1930s) corresponds to high levels of degradation from an influx of agriculture and grazing activities. In these instances, the period of record needs to be viewed within the context of the channel's disturbance history. Although historical and contemporary sources (e.g., aerial photographs, surveys, maps) document changes in channel location and conditions, such sources do not demonstrate causality between physical processes and landscape features. It is a common oversight in historical analyses to focus only on contemporary studies and data and overlook landscape-scale features and processes that are no longer present. This is one of the main purposes of historical studies: to reveal these landscape-scale processes and features that no longer exist due to landscape alteration and fragmentation. Additionally, where structures—such as large dams—have changed sediment supply and the flow regime, it is important, in the context of the historical study, to assess how these structures have changed the fluvial system.

Examination of historical channel change also includes accounting for variability in flooding, sediment and woody debris loading, and human alterations (including changes in land use). In order to prevent over or under representation of channel changes, many studies (e.g., Graf 1981; Gurnell 1997) recommend historical studies should cover time scales of at least 50 years or more when interpreting average rates of channel migration. If historical data is insufficient or unavailable, then the analyst must rely on well-developed field studies to reconstruct past channel movement and rates of channel erosion (see **Appendix B**).

Although HMZs show the minimum extent of the CMZ (excluding DMAs), they are not used alone for CMZ delineation: depending on trends in channel movement, changes in boundary conditions, and the context of the channel's disturbance history, a stream or river channel may have a high likelihood of eroding areas in the future that were previously unoccupied in the historical photo record. Accordingly, measuring rates and directions of historical channel movement are as important as tracing historical channel locations. For this reason, it is best to perform most (if not all) of the fieldwork after the historical analysis is complete in order to gain the most benefit from the results of evaluating historical channel positions and disturbance patterns.

Fieldwork (on-the-ground data collection) primarily consists of describing and mapping geologic, geomorphic, and vegetative conditions in the given area (see **Appendix B**), which includes:

- recording stratigraphic sections along eroding banks (as well as heights of banks);
- documenting the characteristics and erodibility of surficial deposits within and along the stream or river;

- creating a geomorphic sketch map and writing a description of the channel and floodplain conditions, both of which characterize:
  - bank conditions (material properties, slope, vegetation, failure mechanisms);
  - artificial structures (revetments, bridges, deflectors, abutments, levees);
  - in-stream roughness components (woody debris, bars, bed material/texture);
  - side channels;
  - floodplain vegetation (actively eroding areas are highlighted as well as the locations of old channel deposits);
- surveying topographic transects to document relative elevations of channels, floodplains, and terraces, particularly where high resolution topographic data is not available;
- describing conditions upstream and downstream of the project reach (applicable to historical studies, as well); for example, describing:
  - whether or not elevated rates of mass wasting and bank erosion in the watershed will significantly increase the quantity of sediment delivered to the project reach;
  - whether or not development in the watershed is likely to cause increases in the frequency and magnitude of peak flows;
  - whether or not there have been downstream changes in base level that could impact the project site.

Field sheets adapted from Thorne (1998) are provided in **Appendix B** as a resource for describing fluvial characteristics of the project site; the information provided in **Appendix B** is especially useful in those instances where historical data (aerial photographs and historical maps) is unavailable or unusable. The field sheets are followed by notation instructions, as well as an explanation of terms. Information and data chronicled in the field sheets—along with the maps—provide the documentation the analyst uses to support the CMZ delineation. Collectively, the field sheets are intended to be used as a tool for addressing data gaps, not as a *How To* manual for delineating CMZs. They are intended for individuals with training in fluvial geomorphology, given that expertise in fluvial geomorphology is essential for correctly identifying fluvial features, interpreting geomorphic processes, mapping geologic materials, and evaluating erosion and bank stability.

Depending on the purpose of the study and the river system, usable CMZ delineations may be obtained from a less intensive approach than the one presented in this chapter. Graf (2000) provides an example of an alternative approach to CMZ delineation (**Appendix C**) by using past channel locations for calculating the likelihood of future channel occupation (probabilistic analysis of channel location). However, Graf's approach may be inappropriate for evolving systems (i.e., systems that can or will erode into areas not previously occupied in the historical record). Furthermore, this approach is GIS intensive and should be supplemented by field studies to verify the assumptions and results of the probability analysis. (For more information on the limitations of this approach, see **Section 4.1—Limitations of Planimetric Analysis.**) If these limitations are kept in mind, this approach can provide a user-friendly method for calculating erosion risk as long as the analyst can demonstrate that future trends in channel behavior are captured in the areal extent of past channel locations of the historical record.

The remainder of this chapter presents information on delineating the four major components of a CMZ: the HMZ, AHZ, EHA, and DMA. Also included in this chapter is a discussion on determining the relative risks of erosion hazard within the CMZ.

4.1 Delineating the Historical Migration Zone

The Historical Migration Zone (HMZ) is the area the channel has occupied over the course of the historical record and is delineated by the outermost extent of channel locations plotted over that time. Planimetric analysis is used to define the HMZ by overlaying channel positions from the historical record and measuring changes in sinuosity, rates of channel erosion, and directions of channel movement (**Figure 6**). There are two preferred methods for measuring channel planform change: transect measurements and polygon analysis.

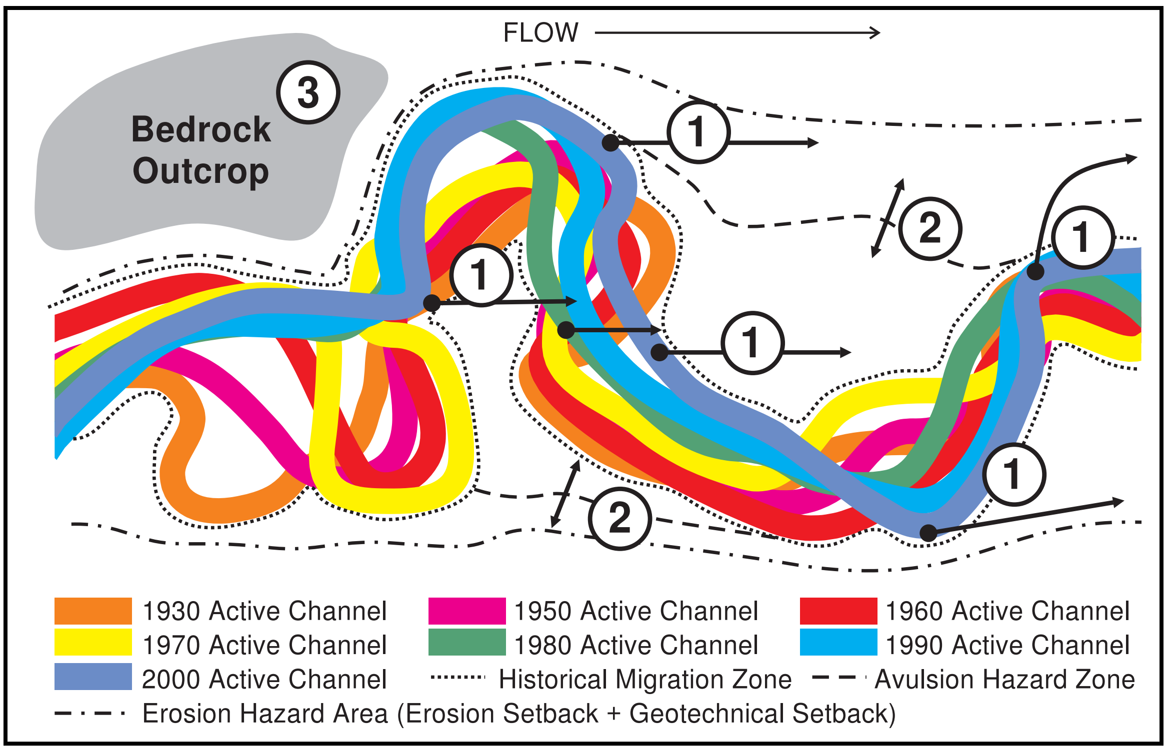

Figure 6. Identifying trends in channel movement from the historical record (e.g., aerial photography, maps) is the most widely available means for interpreting historical channel behavior. Using a conceptual example, from 1930 to 1970, the upstream meander **(1)** became enlarged over time as the neck of the meander became increasingly pinched. At some point between 1970 and 1980, a neck cut-off avulsion occurred **(2)**, which set in motion a series of channel responses farther downstream. Due to the neck cut-off avulsion, meanders **(2)**, **(3)**, and **(4)** are migrating downstream and are eroding into the boundary of the HMZ. Further analysis is needed to determine if avulsion hazards exist at **(5)** and **(6)**.

Advantages of the Geographic Information Systems Platform

The clearest way to measure rates and direction of channel movement over time is to directly compare channel positions by overlaying mapped and photographed channel positions from different time periods. This is most easily and accurately accomplished using the Geographic Information Systems (GIS) platform, the preferred tool for data entry and analysis because it has a number of advantages over manual methods (Gurnell et al. 1994):

- Vector boundaries derived from maps and aerial photos with different scales and distortions can be imported into GIS and registered to the same base map. The process of integrating multiple images at different scales also allows the investigator to quantify any errors that may have been introduced.
- Although data entry in GIS can be time consuming, spatial analyses are more easily made by expanding the possible range of comparisons, predefined spatial resolutions, and indices.
- Besides providing a format for quantifying channel change, GIS also provides visualization capabilities, like map production and graphical outputs.

Aerial Photograph and Map Registration in GIS

The first step in measuring channel change over time is to minimize any errors that may be incurred from registering and interpreting aerial photos in GIS. Gurnell (1997) suggests five strategies for minimizing errors when comparing information extracted from aerial photos of the same channel over different dates:

1. Use aerial photos with similar scales; if scales between data sets vary (e.g., 1:10,000 to 1:24,000), aerial photo sets may be printed at different contact scales to more closely resemble other data sets (e.g., 1:24,000 printed at 1:11,500).
2. Use the same person to interpret aerial photo sets and provide written documentation of their methods and assumptions.
3. Use a set of standard control points (see note below) to register information from each set of photographs to a common base. Current studies recommend 15-25 control points for registering each individual photograph (e.g., Gurnell 1997, Graf 2000).
4. Use a standard non-linear least-squares transformation to register photos to a base map. This method allows as large an area of each photo as possible to be registered to the base map, and therefore allows the largest possible number of control points to guide the registration. The residuals generated by this method indicate potential errors by comparing the same location at different dates, and therefore enable the investigator to gage to what degree changes in river bank locations represent true channel changes.
5. Use a standard definition for river bank location. Depending on the geomorphic and vegetative setting, a definition using vegetative indicators may be more appropriate in areas with a fluvial-tidal transition. However, in freshwater settings, morphologic definitions are more appropriate, especially if overhanging trees obscures images. Either way, it is important to use criteria that are consistent between each data set. For instance, the unvegetated channel is more consistent to use than the wetted area because the unvegetated channel represents recent bed disturbance independent of flow conditions at the time of the aerial photo. The wetted area of the channel is only meaningful if the investigator has flow estimates for all of the aerial photographs used in the analysis, and even then it only provides an approximate means for estimating changes in thalweg location. (If possible, this is also an opportunity to digitize the thalweg for each data set, which can be later used to approximate water surface slope

from LiDAR DEM. Comparison of thalweg locations can complement comparisons of active channel locations.)

Note: A relatively large number of fixed control points are used to geometrically correct and register data sets because ortho-rectifying aerial photos requires careful attention, given the degree of distortion from the angle of the sun, from the steepness of the terrain, and from the camera lens. Fixed control points need to provide precise latitude-longitude coordinates that can be found between data sets, such as grid intersections, corners of buildings, road intersections, and bridges. Features (e.g., man-made constraints, channel planforms) may be digitized on-screen after data sets have been scanned into GIS. Accordingly, reliably digitizing the active channel requires numerous control points and an individual with basic image processing skills (the ability to enhance the image for better visual interpretation), and familiarity with the field conditions (i.e., direct involvement with the field surveys). *If possible, the same staff should perform both the field surveys and the historical studies in order to further improve the accuracy of image interpretation and the location of features of interest on the ground.*

Limitations of Planimetric Analysis

Though some methods for measuring planform change capture more detail than others, all planimetric analyses share the following limitations:

- Poorly registered images compounded by inconsistently defined channel features can cause substantial errors in measuring erosion rates. The investigator should take special care in accurately registering aerial photographs and maps into GIS. The analyst must also consistently delineate the extent of fluvial features between data sets.
- By themselves, planimetric analyses only document geographic changes, from which on-the-ground channel processes are inferred. Planimetric analyses do not explicitly account for the effects of bank material, soils, vegetation (in the channel, on the bank, on other alluvial surfaces), sediment and discharge, and man-made structures. Field studies, in combination with key background information (e.g., geology map, hydrologic records, inventory of man-made structures), are essential for refining forecasts of channel behavior.
- Planimetric analyses do not account for or allow measurement of vertical channel movement.
- Planimetric analyses may be difficult to implement on smaller streams.
- Depending on the resolution of the data, active features (e.g., secondary channels) that are subject to channel occupation may be obscured in the photo record. Field visits are necessary to identify these features.
- Planimetric analysis can over or under represent channel changes when the period of record is too short to capture climatic variability that occurs over time. Most studies suggest at least 50 years of remote sensing data (preferably at intervals of five to ten years) are necessary to reveal meaningful trends in channel change and bed-material transport rates (Graf 1981; Graf 2000; Gurnell 1997; Ham and Church 2000).

4.1.1 Sources of Information

- Aerial photographs,
- Digital Elevation Models (DEMs)
- Light Detection and Ranging (LiDAR) data
- Orthophotos (Department of Natural Resources)
- U.S. Geological Survey (USGS) topographic maps
- Government land survey records
- U.S. Coast and Geodetic Survey (USC&GS)
- Settlers accounts
- Contemporary histories (e.g., Interstate Publishing Company 1906)
- Photographs (historical societies, library)

For more information (including explanations and definitions), refer to **Appendix D: Sources of Information**.

4.1.2 Transect Measurements

The use of transects for measuring channel change is well established in peer-reviewed literature (e.g., Hickin and Nanson 1975; Pizzuto 1994; Gurnell et al. 1994; Gurnell 1997). Although transect measurements can be taken manually or in GIS, the advantage of digitizing transects in GIS is that it allows for the systematic measurement of spatial and temporal channel change without introducing the bias that typically occurs from manually measuring specific features, such as channel bends.

Two types of transects are used at the same time for calculating changes in channel locations: floodplain transects and active channel transects. The active channel transect is the sum of the widths of the actively flowing channels plus the unvegetated bars. The floodplain transect is defined as the Holocene valley bottom, which can be identified using geology maps and DEMs or LiDAR (Holocene is defined as the time period encompassing the last 8,000 years to the present). Overlaying the centerline of the active channel transects with the centerline of the floodplain transects enables the investigator to calculate erosion, deposition, and avulsion over the period in question. Measurements are taken from one data set to the next to calculate rates and directions of channel movement over the course of the timeline being studied.

Floodplain transects are digitized perpendicular to the centerline of the valley bottom, and provide the analyst with a means for measuring and delineating broad-scale attributes, such as:

- channel sinuosity
- valley width
- active channel width(s)
- location of the primary active channel
- locations of historical channels and secondary channels

Active channel transects are used to quantify the rate and direction of channel movement, and are digitized perpendicular to the centerline of the primary low-flow (widest wetted) channel at discrete increments scaled to the size of the channel (**Figure 7**). For each transect, the investigator measures width and area of the primary low-flow channel and the width, area, and number of other connecting channels, such as side channels. The width and area of unvegetated gravel bars (e.g., filled-in side channels or sloughs) and isolated (from the main channel) or partly isolated water bodies (e.g., oxbow lakes) are also measured. (Isolated or partly isolated water bodies are defined by their connectivity to the primary low-flow channel: isolated water bodies are disconnected at both ends, whereas partly isolated water bodies are only disconnected at one end.) As with all planimetric analyses, field studies are essential for verifying unstable banks, side channels, isolated water bodies, and partly isolated water bodies that were viewed in aerial photographs.

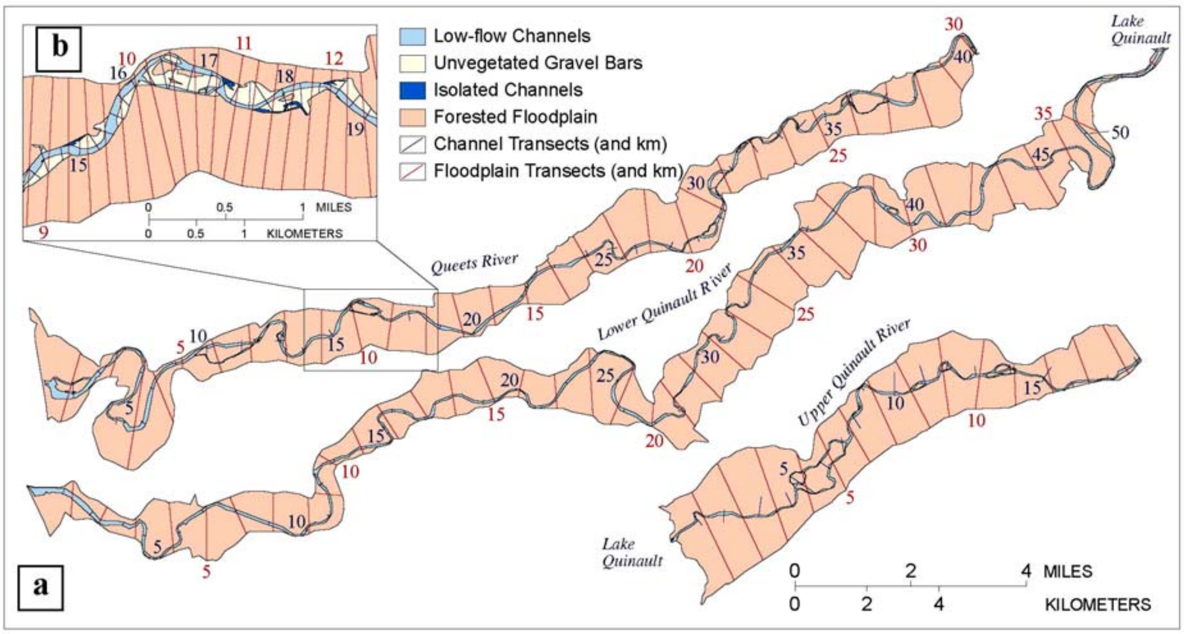

Figure 7. The location of the active channel is depicted within the Holocene valley bottom (labeled as the forested floodplain). Floodplain and channel transects remain stationary through each set of aerial photographs for measuring rates of erosion, tracking directions of channel migration, and documenting changes in channel features (O'Connor et al. 2003).

Floodplain transects and active channel transects remain stationary for each set of data when tracking rates and directions of channel migration over time. Erosion rates developed in the study can be used to extrapolate future erosion rates. The end product of this method is a map that depicts the HMZ (**Figure 8**) within the valley bottom that is accompanied by estimates of erosion rates, both of which provide a basis for evaluating future trends in channel movement.

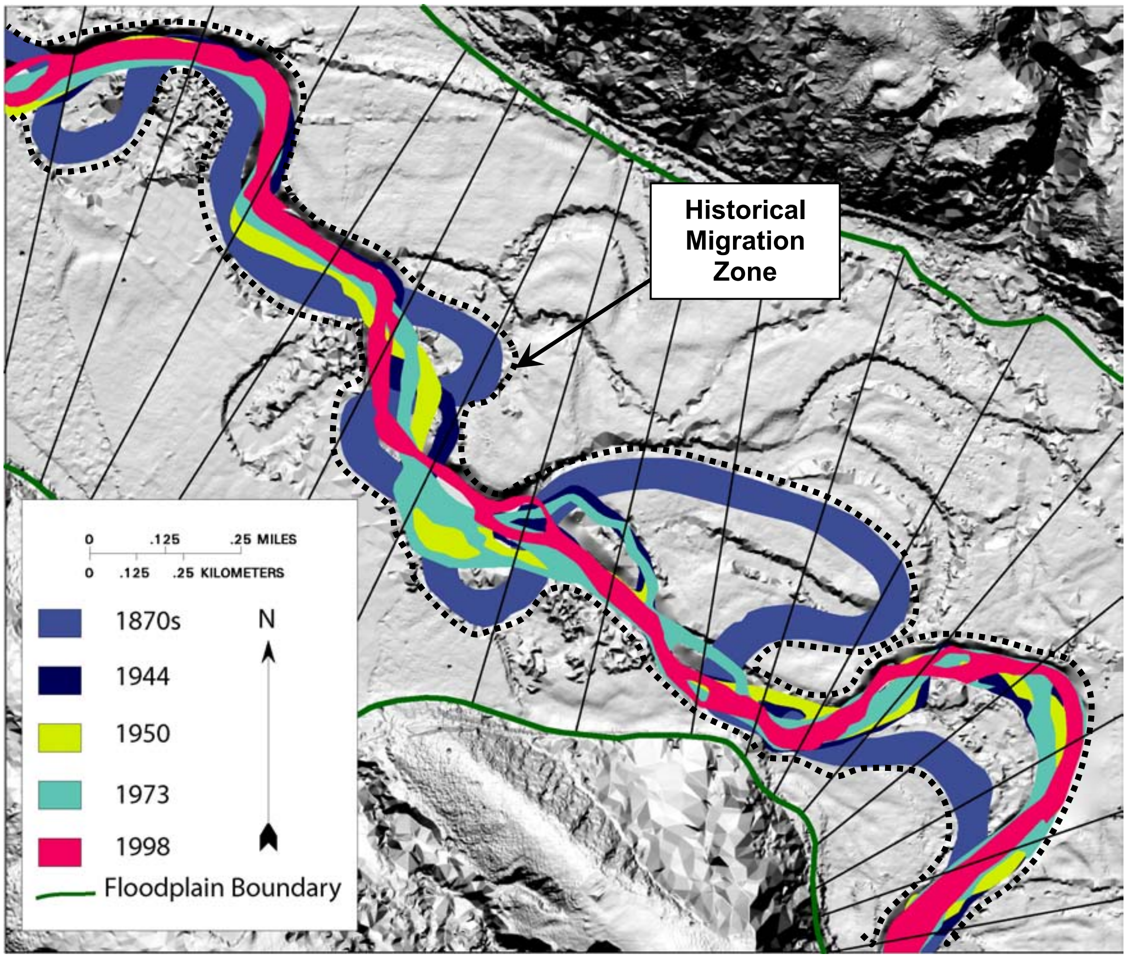

Figure 8. The HMZ is depicted within the valley bottom as the outermost extent of all documented historical channel locations. The relic channels on the LiDAR image that are not included in the HMZ were occupied by the channel prior to the historical record; therefore they are not included in the HMZ. (Graphic adapted from Jim O'Connor.)

Advantages
This method allows for the systematic measurement of channel change if the investigator does not have access to GIS.

Limitations
The distance between transects must be tailored to the size of the stream, otherwise the resolution of measurements may not adequately capture the extent of channel change occurring over time. Because this method predates GIS it does not take full advantage of computerized areal analyses that are now possible, such as using polygons (**Section 4.1.3**).

For more information, refer back to **Section 4.1—Limitations of Planimetric Analysis**.

4.1.3 Polygon Analysis

The use of polygons (**Figure 9**) as an analytical tool for measuring changes in the areal extent of fluvial features (bars, active channel, islands) is also well established in peer-reviewed literature (e.g., Piégay et al. 1996, Jacobson and Pugh 1997, Graf 2000, Ham and Church 2000, and O'Connor et al. 2003). Analyzing areal changes in channel features is best accomplished using GIS, given the necessity of rectifying and overlaying aerial photographs. Polygon-based analysis has the distinct advantage of capturing the full extent of channel changes and utilizing the automated functions available in GIS. Assuming GIS is available, polygon-based analysis is preferred over transect measurements because changes are measured areally rather than linearly. Polygon-based analysis also allows the calculation of floodplain turnover rates (described below). If GIS is not available, then transect measurements would be utilized.

Polygon analysis follows three basic steps:

1. scan and register remote sensing data (aerial photographs, maps) into GIS;
2. digitize channel and floodplain features as polygons for each data set; and
3. use areal changes between sets to calculate erosion rates and estimate floodplain turnover rates for each channel reach.

The floodplain turnover rate—used for estimating the EHA discussed in **Section 4.3**—defines the amount of time it takes for a channel to occupy its entire valley bottom (O'Connor et al. 2003). In some systems, the river may occupy its entire valley bottom within a period of decades, while other systems may have floodplain turnover rates that extend over centuries.

Digitizing channel features is limited to the geomorphic surfaces that are consistently identifiable between each data set (**Figure 9**). At a minimum, the active channel(s) and the Holocene floodplain are mapped as polygons for each reach over the historical period of the study. The investigator can also use stereo-pairs of sufficient resolution to digitize bars, islands, man-made structures, and terraces, in addition to the active channel. Mapping these other channel features can be useful for estimating the effects of causal mechanisms on channel migration; as always, field visits are essential for educating the investigator on the appearance and common occurrence of each type of channel feature identified on aerial photographs (Graf 2000). The types of attributes that are used by the analyst over each record of channel position depend on which characteristics are consistently identifiable over the historical time period in question and on the objectives of the study. For example, the authors of **Figure 9** have tracked changes in attributes for cropland, grassland, woodland, gravel, and channel, while Ham and Church (2000) used a more process-based attribute system that included erosion, stripping, recovery, stable, and deposition. Linking historical channel migration with current alluvial stratigraphy allows the analyst to interpret past channel behavior and anticipate the variability of future channel conditions.

For each record of channel position, the analyst calculates:

- the total area of the active channel;
- the area of the channel outside the area of previous record; and

- the area of channel outside all past channel locations.

These results allow the analyst to assess how the total channel area has changed over the historical time period and to evaluate what proportion of new channel area of each map data represents erosion of historically uneroded floodplain (as opposed to reoccupying previous channel locations).

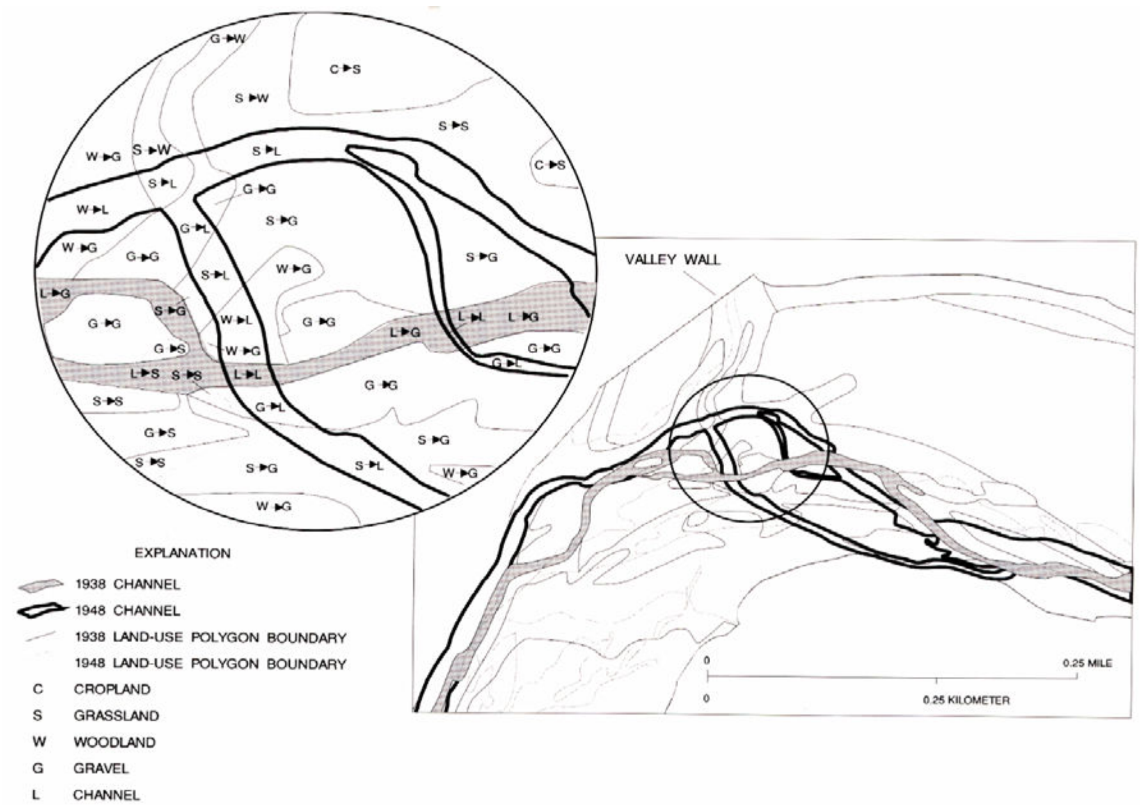

Figure 9. Example of using polygons in GIS to identify changes in attributes between two data sets (Jacobson and Pugh 1997).

Advantages
Polygon-based analyses can capture the full extent of channel change as long as the channel features are accurately and consistently digitized. This method also provides the basis for estimating floodplain turnover rates (O'Connor et al. 2003).

Limitations
This method requires the use of GIS.

For more information, refer back to **Section 4.1—Limitations of Planimetric Analysis**.

4.2 Delineating the Avulsion Hazard Zone

The Avulsion Hazard Zone (AHZ) includes the areas of the river landscape, such as secondary channels, relic channels, and swales, that are at risk of channel occupation outside of the HMZ. The purpose of delineating avulsion hazard zones is to anticipate possible shifts in channel location that may threaten infrastructure and necessitate bank protection (**Figure 10**).

Many transportation corridors (roads) have unforeseen long-term economic costs due to unanticipated shifts in channel location. For example, an avulsion on the Middle Fork Nooksack River recently relocated the river channel from the west side of its valley to the east side, placing road at severe risk (**Figure 11-a; Figure 11-b**). The new channel rapidly eroded into an alluvial bank and created a vertical bank face approximately 13 m in height (**Figure 11-c**), which is also within 10 m of a county road. Consequently, the only feasible solutions are to either construct expensive bank protection to halt the erosion and stabilize the bank, or relocate this segment of the road. Delineating the AHZ within a CMZ provides transportation managers, engineers, and planners a valuable tool for identifying risk areas and strategically locating new roads to reduce future economic risk.

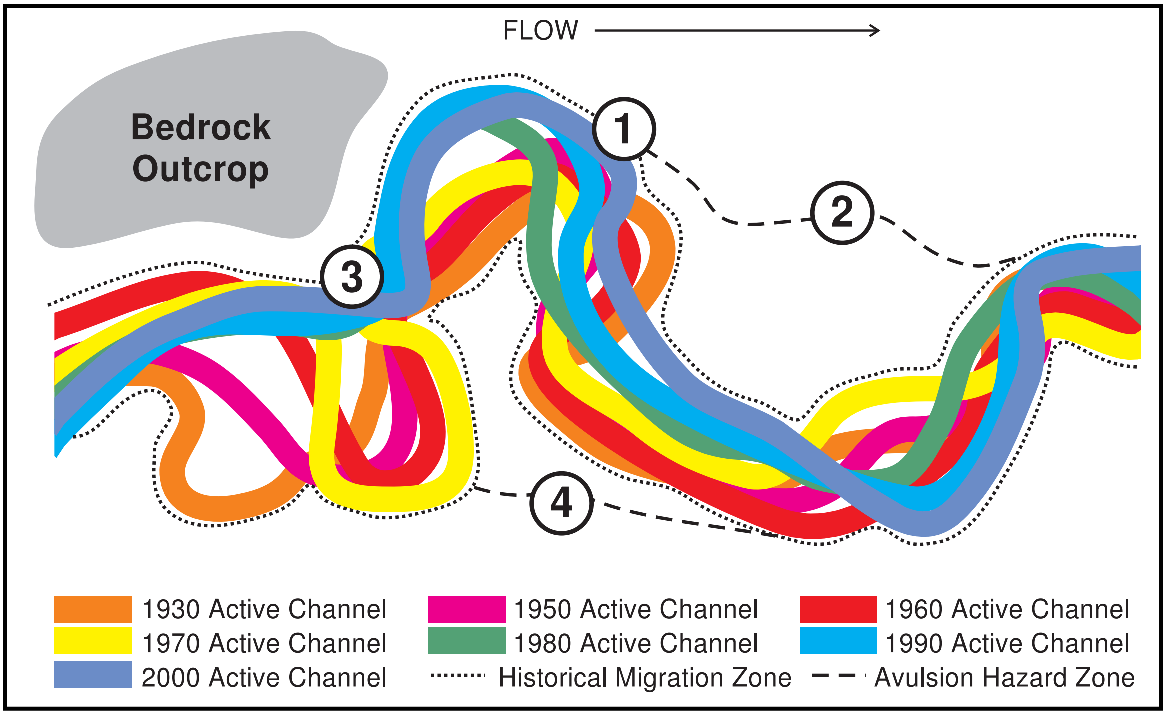

Figure 10. In this conceptual example, field studies combined with hydraulic modeling established two avulsion hazards. The first avulsion hazard is an abandoned channel **(2)** that lies adjacent to the active channel eroding into the HMZ **(1)**; field evidence of aggradation initiated by log jams and the elevation and topography of the abandoned channel provides a preferential flow path for the river. The second avulsion hazard connects an abandoned meander to the HMZ **(4)**; although the channel avulsed away from the 1970 channel **(3)**, the avulsion hazard **(4)** exists given that perturbations upstream of this reach may cause the channel to reoccupy the 1970 channel within the design life of the CMZ. Likewise, the EHA takes into account bank erosion of **(2)** and **(4)** in order to anticipate channel occupation of relic features.

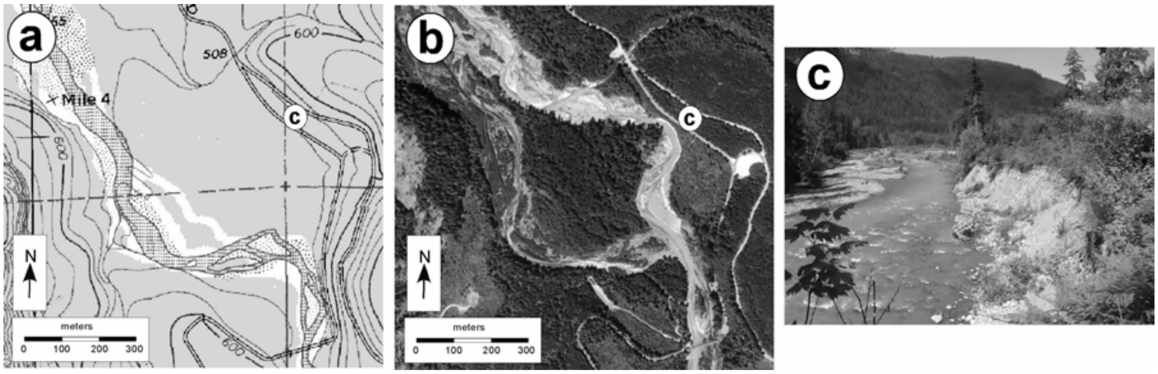

Figure 11. An avulsion during the 1990s relocated the Middle Fork Nooksack River from the western to the eastern margin of its valley (~540 m), as seen in this 1991 map **(a)** and 1998 airphoto **(b)**. The channel proceeded to erode into an alluvial bank, 11 m in height and within ~10 m of a county road in 2001. The eroding bank (composed of glacial outwash) is depicted in photograph **(c)**, looking downstream (northwest). The river is flowing to the northwest and is located in Whatcom County.

Delineation of the AHZ relies primarily on three field-based steps:
1. Estimate vertical variability of the channel bed by assessing bank stratigraphy and the influence of LWD on channel dynamics.
2. Survey general characteristics of riparian vegetation.
3. Map secondary channels, swales, and relic channels at risk of current or future channel occupation.

4.2.1 Sources of Information

The analyst should supplement the following information with the appropriate field investigations:
- HMZ determination
- Trends in channel movement and rates in channel movement
- Aerial photographs
- U.S. Geological Survey (USGS) topographic maps
- Geology maps: USGS and state resource agencies
- Streamflow data (flood events): USGS gaging stations: http://waterdata.usgs.gov/wa/nwis/nwis
- Digital Elevation Models (DEMs)
- Light Detection and Ranging (LiDAR) data
- Cross-section and profile data for assessing background changes in the channel bed elevation: FEMA or Army Corps of Engineers Flood Insurance Study maps and raw stage data from USGS gaging stations
- Available hydraulic models completed by federal agencies (USACE, FEMA) and consulting firms (e.g., HEC-RAS, HEC-2, Mike 11, WinXSPro)
- Field sheets (**Appendix B**)

For more information, refer to **Appendix D: Sources of Information**.

4.2.2 Estimating Vertical Variability of the Channel Bed

The bed of a channel may rise (aggrade) and fall (incise) as it adjusts to fluxes in woody debris, sediment loading, and flooding activity within the system. Activities that initiate aggradation (and therefore increase avulsion hazards) include log jam formations, dams, or landslides (including debris torrents and deep-seated landslides) that impound the channel. As a channel aggrades, flooding occurs over greater areas of its floodplain, thus activating relic channels, swales, and secondary channels. On the other hand, long-term incision (caused by splash damming, log jam/snag removal, dredging, channelization, or dredging) causes a channel to abandon its floodplain, which diminishes avulsion hazards. However, incised channels may still be unstable, given incision often initiates a period of channel widening as unstable banks collaps (see **Figure 5**).

Primary sources of data for assessing vertical variability include:

- empirical observations of bank stratigraphy and the role that woody debris plays in channel dynamics;
- current surveys of pre-existing cross-sections (from flood studies, consulting reports, agency reports, and raw USGS gage data); and
- any available hydraulic models that link water surface elevations with specific flood events.

Knowledge of how streams are affected by their environment is also useful for understanding vertical variability. Streams in their natural state, with relatively undisturbed forested catchments and riparian zones, are likely to experience significant fluctuations between incision and aggradation in response to naturally occurring fluctuations in sediment supply and woody debris loading. On the other hand, streams that drain catchments that are being disturbed by land management activities (such as industrial forestry) are susceptible to aggradation due to high levels of erosion and mass wasting. Channelized streams, streams that have been cleared of woody debris, and streams with highly urbanized catchments are susceptible to irreversible long-term incision due to corresponding increases in discharge and decreases in channel roughness and sediment inputs.

Assessing Bank Stratigraphy

It is important to identify the geologic context of alluvium along the channel in order to differentiate modern stream deposits (from the last 5000 years) from deposits associated with other climates and processes (e.g., glacial or volcaniclastic deposits). In terms of channel bed dynamics, modern fluvial banks can provide context for the extent of modern channel processes (e.g., historical incision, cycles of aggradation and incision, frequency of flooding). One way to distinguish recent fluvial materials from glacial sediments is to identify deposits that are unambiguously modern and use them to evaluate less identifiable deposits. For instance, sediment transported and deposited within the channel differs from finer sediments deposited on floodplain surfaces. Accordingly, it is important to describe the size distribution of the materials found in the bed and bars of the active channel and to examine eroded banks where alluvial stratigraphy is exposed. Distinct layers of alluvium correspond to different materials found in an active fluvial system. For instance, bedload in montaine channels is often deposited as thick layers of imbricated gravels, whereas overbank flood deposits form relatively homogeneous layers of sands that overlay the gravels.

Glacial deposits (till, moraines, outwash) can be distinguished by their tendency to exhibit some weathering (staining on grain surfaces), as well as distinctive sedimentology and stratigraphy. Till deposits tend to be poorly sorted and have anomalously large clasts. Moraines occupy particular areas of a river valley and often have boulders large enough to withstand the transport capability of the present day channel. Although glacial outwash can be more difficult to distinguish from modern alluvium, since it has been deposited by flowing water, it can be identified by its weathering, color, internal stratigraphy, and relative thickness. Outwash deposits are typically more than 20 m in thickness and generally deposited as braided channels, which leave behind a sedimentology and internal stratigraphy that is different from modern meandering and anastomosing channels (e.g., outwash deposits are unlikely to have overbank or floodplain deposits commonly associated with most modern alluvial rivers). Additionally, deposits formed in glacial lakes (temporary impoundments in the ancient river valley) typically consist of thick deltaic sequences of sand and layered lacustrine silts and muds, deposits that can be readily distinguished from those formed by the modern river.

As an example, **Figure 12** shows an eroding bank along the Hoh River. Both the bed material and overbank sediments in the bank reflect those found in the active channel of the Hoh River. The height of the relic channel above the current river indicates there may have been some significant incision within this reach of the River. In this scenario, the analyst needs to determine whether trends in incision are recent, whether they will continue, or if they are reversible under current and future conditions. The CMZ analyst can use the field sheets in **Appendix B** to record the physical characteristics, spatial extent, and probable origin of surficial materials within the study area.

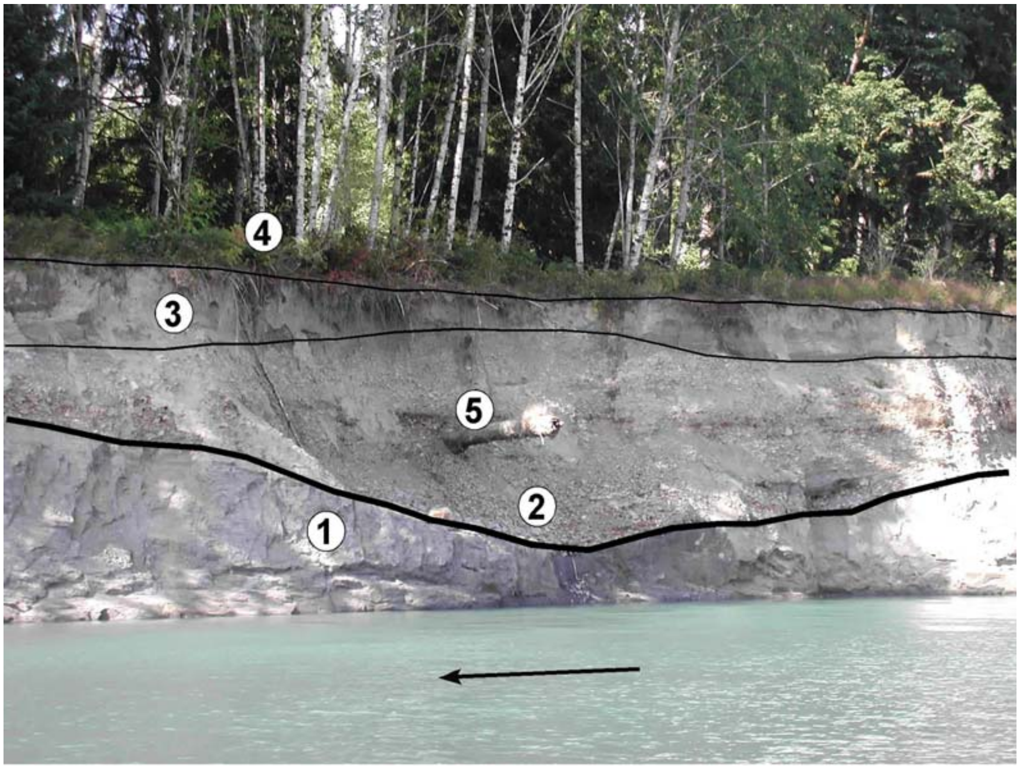

Figure 12. Eroding bank along Hoh River, Jefferson County; flow is right to left. Bank stratigraphy consists of a lower layer of Quaternary (>10,000 years old) lacustrine clays **(1)** overlain by channel gravels **(2)**, overbank sand **(3)**, and the duff layer of the young Alder (*Alnus rubra*) forest on the floodplain surface **(4)**. The cross-section of a relic channel, which incised into the underlying clay, is exposed in the bank stratigraphy **(2)** indicating the channel once flowed perpendicular to the current channel. The channel filled with bed material (imbricated gravel) and was incorporated into the floodplain. Prior to the channel being abandoned, a snag was deposited in the middle of the channel—its crown sticks out from the bank **(5)**, indicating this reach of the Hoh River may have incised.

Assessing Large Woody Debris

In forested river systems, log jams can impose significant changes to a channel by affecting floodplain and terrace development (Hogan 1987; Abbe 2000; Lancaster et al 2001; Abbe and Montgomery, 2003). The size of fallen trees relative to the channel, the supply of wood within the system, and channel substrate all influence the probability of log jam formation (Abbe 2000, Lancaster et al 2001; Abbe and Montgomery, 2003). The greatest change in streambed elevation from log jam formation tends to occur in second to fourth order channels with bankfull widths less than the height of fallen trees and valley gradients of 0.02–0.10 (Abbe 2000). Additionally, the relief created by log jam formation gradually diminishes with channel size and valley gradient. The CMZ analyst can therefore use historical information and empirical data from analogous sites (including sites reflecting future projected riparian forest conditions for the study reach) to estimate the potential vertical change in a system.

The CMZ analyst can also estimate the effects of log jams on vertical bed movement by observing the degree of aggradation that occurs upstream of log jams within the same reach. Exposed bank stratigraphy composed of channel bed gravels may indicate the elevation of the channel prior to the failure of a log jam. When log jams have clearly forced channel bed aggradation in other areas of the reach (and there is a supply of mature woody debris), then LWD is likely responsible for cycles of aggradation and incision that occur within the reach. Consequently, sequences of channel bed gravels in bank stratigraphy may represent the upper extent of aggradation that occurs over the design life of the CMZ.

According to Abbe and Montgomery (1996), Abbe (2000), and Abbe and Montgomery (2003) vertical fluctuations in channel elevation are generally equivalent to at least one rootwad diameter or two to three basal diameters of mature riparian trees. Likewise, up to 2 m of initial vertical aggradation are likely to occur in forested rivers where snags and log jams will form; additional aggradation becomes gradually less probable depending on the size of the channel, the size of recruitable wood, and confinement (**Figure 13**). Note that streams and rivers which have been channelized, or in which wood has been cleared or will continue to be cleared, are more likely to incise, not aggrade (depending on sediment flux associated with surface erosion and mass wasting). The CMZ analyst should carefully consider historical and current conditions to predict future change associated with woody debris loading.

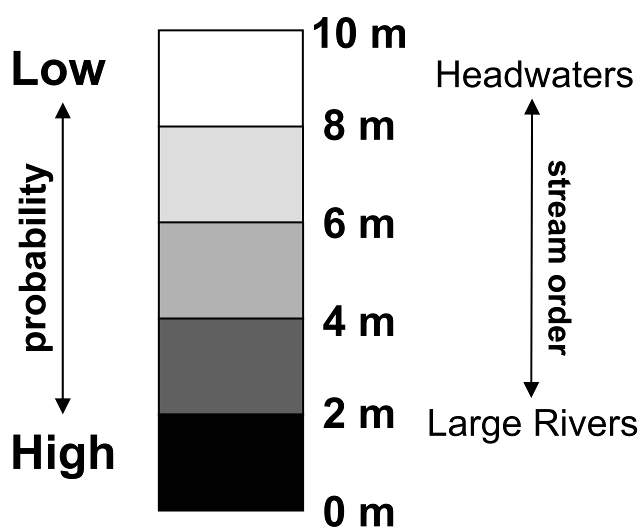

Figure 13. This chart is a general guideline for predicting potential vertical variation in forested streams and rivers based on Hogan (1987), Abbe and Montgomery (1996), Abbe (2000), Lancaster et al (2001), and Abbe and Montgomery (2003), given that vertical variation in channel bed dynamics linked to woody debris depends on the size of the channel, the size of recruitable wood, and confinement.

In large rivers, 2 m of vertical variation can be common due to variations in sediment supply and flow. The analyst can assume that vertical channel fluctuations of 2 m will likely occur in forested systems and systems with riparian buffers; however, the probability for additional vertical change depends on the size of the channel, the size of recruitable woody debris, and confinement of the channel. For example, the Hoko River log jam described later in this section raised the channel bed over 2 m in less than one decade, persisting through several record flood peaks. The log jam located within the reach is likely to remain intact for many years, continuing to raise the river channel before the river finally cuts a new path and abandons the log jam.

Assessing Probability of Inundation

Typically, modeling based on fixed-bed hydraulics (HEC-RAS) is used to estimate the probability of secondary channels, swales, and relic channels becoming inundated during certain peak flow events. However, this approach may not capture areas at risk of inundation for channels subject to vertical changes in their channel bed elevation or for channels experiencing changes in their flow regimes (due to urbanization or flow regulation). In these cases, the analyst can augment hydraulic modeling with scenarios that incorporate a maximum elevation for aggradation as well as placing the channel bed at different locations (as might occur from avulsion or channel migration) within the valley bottom. If pre-existing cross-sections are not available, the analyst can survey cross-sections within the study area and use empirical observations to approximate the upper limit of channel aggradation.

For more detailed discussions of hydraulic modeling please refer to Maidment (1993).

By using USGS gaging data to estimate the relative magnitude of the last flood event, the analyst can link field indicators, such as flood debris (trash, organic debris), silt lines, and flattened vegetation, to evaluate the extent of inundation associated with the last flood event. Trash and organic debris often catch on fences, trees, and shrubs during the receding limb of the flood hydrograph. Trash and organic debris tend to degrade quickly, allowing their condition to act as a guide for estimating the time that has elapsed since the last flood event. Additionally, flood waters often plaster silt in moss growing on the stems of riparian vegetation or directly on the bark of the tree trunks. Determining whether or not silt lines are recent depends on the condition of the surface it rests on—often a distinction can be made between moss that has grown over silt plastered in previous floods from silt that rests on its surface. Flattened vegetation refers to stems that have been flattened to the ground, usually all in the same direction, from channel flow moving downstream.

Notably, the upper extent of relatively fresh flood debris, silt lines, and flattened vegetation marks the minimum water surface elevation of the last flood event. In evaluating field evidence, the analyst should rely on several lines of evidence that can be used to corroborate the presence of each other. An absence of flood debris or silt lines above bankfull stage indicates that either the river has incised or that engineered flood protection structures have affected the system. On the other hand, channels with no record of a recent medium-sized or large-sized floods that possess fresh flood debris or silt lines above the bankfull stage indicates that out-of-bank events occur frequently.

4.2.3 Surveying Riparian Vegetation

The riparian corridor has long been recognized for providing important ecological habitat, and more recently for other beneficial functions. A riparian buffer creates space within which river form and process can be allowed to adjust freely. Riparian buffers increase resistance to bank erosion and provide lateral stability by reducing near-bank velocities, reinforcing the bank material, and limiting access to grazing animals. Channel banks are more prone to erosion when the buffering effects of riparian vegetation are lost to agriculture, heavy grazing or floodplain development that extends up to the bank edge. Riparian buffers intercept and detain surface runoff, reducing the potential for erosion over and through the bank, acting as a sink for pollutants, and improving in-stream water quality. For these reasons, the existence and extent of the riparian corridor is an important indicator of channel condition, sensitivity to change and management status (Thorne 1998).

The importance of vegetation in the fluvial environment has been well documented, especially in regards to its role in erosion control (e.g., Smith 1976; Simon and Hupp 1990; Simon et al. 1999; Abernethy and Rutherford 2000, 2001; Simon and Collinson 2002), bank stabilization (e.g., Thorne 1990, Simon and Collinson 2002), bank protection (e.g., Smith 1976, Swanson and Lienkaemper 1982), and bank accretion (e.g., Thorne 1990, Hupp 1992). For example, several studies have demonstrated that converting pasture to forest along creeks results in significant morphologic changes to the channel, including increased channel variability and widths (e.g., Davies 1997; Trimble 1997; Allmendinger et al. 2000). Descriptions of current riparian conditions are therefore necessary for assessing how current and future riparian conditions may influence the channel. Within the context of Washington streams, riparian buffers may provide key pieces for self-sustaining log jams within 50−100 years (Collins and Montgomery 2002), though current riparian conditions may be dominated by immature trees.

Given that both engineers and geomorphologists recognize the significance of bank vegetation in relationship to bank morphology, erodibility, and stability, the CMZ analyst is encouraged to note the following vegetative characteristics in pertinent reaches of the study area for purposes of delineating the EHA (for more information see **Appendix B**):

- vegetation communities
- tree species
- density and spacing
- age

By providing information on vegetative characteristics, the analyst can determine which secondary channels, swales, and relic channel features are prone to avulsion due to the removal of vegetation or from a lack of vegetative succession.

4.2.4 Geomorphic Mapping and Representative Cross-Sections

While taking into account the variability of channel bed, vegetative dynamics, probability of flooding, the CMZ analyst should have a basis for determining which secondary channels, swales, and relic channels are susceptible to flood inundation. The next step is to create a geomorphic map that documents the locations and characteristics of these channel features (**Appendix B, Section 3**). The channel sketch map is used to document forms and features of the active channel(s) and channel features not readily seen from the aerial photograph record, such as secondary channels. The channel sketch map and representative cross-section components of the field sheets allow the analyst to capture:

- the number and extent of secondary channels for all alluvial surfaces
- the elevations of secondary channels, swales, and relic channels relative to the elevation of the active channel bed
- the estimated maximum elevation of the active channel bed
- the type and extent of vegetation communities on all alluvial surfaces
- the current extent of bank erosion
- the type and extent of artificial constraints acting on the channel
- the locations and influence of log jams and woody debris on channel migration and vertical channel movement

The geomorphic map also records the locations of sampling points for bed and bar sediment samples and cross-sections. In addition, photographs should be taken to show:
- views upstream and downstream along the study reach
- the right and left banks
- any special features of the channel

Photograph points and orientations should be marked on the map so that photographs can be precisely re-taken in any future surveys. This greatly enhances their value as a guide to channel changes such as bank erosion or vegetation succession (Thorne 1998).

The channel sketch map and representative cross-section of the **Section 3—Channel Description** field sheets in **Appendix B** provide space for visual representations of the channel in the study reach; see **Figure B-7** for an example sketch map and representative cross-section for a reach of the Snake River.

4.2.5 Example: Hoko River, Olympic Peninsula

The Hoko River, located in the northern portion of the Olympic Peninsula, is similar to many rivers throughout Washington State in that it is a forested, gravel-bedded river that is morphologically influenced by LWD. Like many rivers throughout Washington, the Hoko River's fluctuations in hydrology, sediment, and woody debris loading initiate cycles of aggradation and incision as stable log jams form, survive multiple floods, and ultimately fail. The Hoko River, therefore, provides an opportunity for illustrating how stratigraphy, log jam formation, topography, and vegetation can be used to approximate the variability of channel bed dynamics and identify an avulsion hazard.

In **Figure 14**, the downstream views of the Hoko River's right and left bank stratigraphy can be used to evaluate the range in which the channel bed aggrades over time. The two views show how the elevation and relative thicknesses of geologic sequences (imbricated channel bed gravels and overbank sand) have changed within the same cross-section of river. Along river right (**Figure 14-2**), floodplain sands approximately 2 ft in thickness overlay imbricated channel bed gravels approximately 4 ft in thickness. Along river left (**Figure 14-3**), the stratigraphic materials are identical, but the elevation of the horizon between channel bed materials and floodplain deposition is about 3 ft higher. Although the difference in heights between right and left banks seems to suggest that the left bank is a terrace, the geology of the left bank is actually the product of modern channel and floodplain processes: a channel-spanning log jam located nearby has initiated recent channel aggradation almost 3 ft above the level of the exposed bed material/floodplain along the right bank, an elevation that is equivalent to that of the left bank. Within the context of the Hoko River, woody debris is therefore the primary mechanism for vertical channel change. Also, considering the Hoko River's geology, as well as the influence of LWD in this reach, the left bank is still part of the active floodplain, even though the river has temporarily incised at this location.

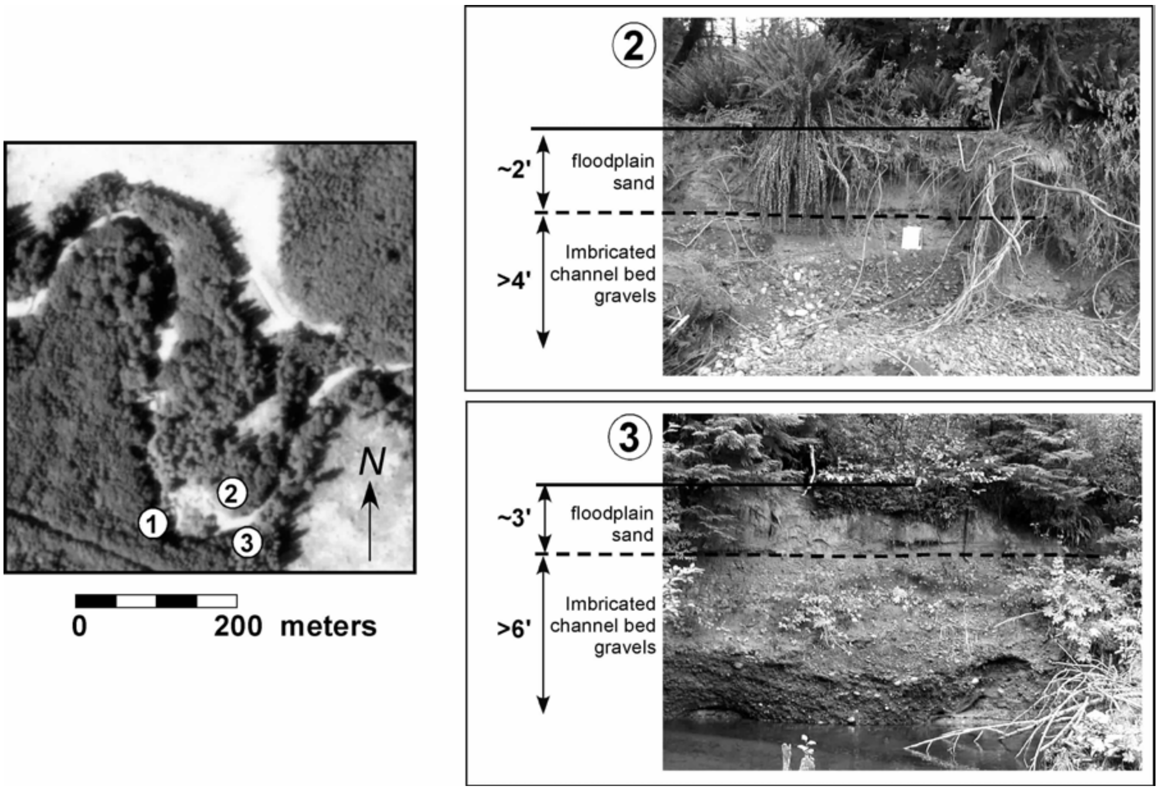

Figure 14. Bank stratigraphy of the Hoko River (aerial photo inset 2000). River flow is from right to left. Bed material (gravel), overlain by floodplain deposition (overbank sands), is exposed in the stratigraphy of the Hoko River; location **(2)** is on river right of the Hoko River (looking downstream) and location **(3)** is on river left (see inset). The only difference between the two sites is the elevation of the channel bed material and floodplain deposition: the elevation of the horizon between channel bed materials and floodplain deposition is ~ 3 ft higher on river left than on the same horizon on river right. A channel-spanning log jam located nearby **(1)** has initiated recent channel aggradation almost 3 ft above the bed material/floodplain horizon exposed on river right. Additional channel aggradation could increase inundation frequency of high banks (thereby converting terraces to floodplains).

The difference in height between the right and left banks offers the analyst empirical data for estimating the range of vertical channel change that regularly occurs in this reach of the Hoko River. This in turn allows the analyst to determine which secondary channels convey flow and could potentially develop into the main channel within the design life of the CMZ. When the analyst delineates the CMZ for this reach, secondary channels found at the elevation of the top of the left bank should be noted as active features that could potentially convey the main channel at some point in time.

Accordingly, the analyst should also note topography, elevation, and vegetative characteristics of secondary channels, swales, and relic channels in order to determine where avulsion may preferentially occur. For example, as the channel-spanning log jam (**Figure 15**) continues to grow, subsequent channel aggradation may initiate a channel avulsion through the abandoned channel. Geologic evidence (indicating vertical channel instability) and field observations (linking woody debris as the mechanism), as well as the topography and elevation of the relic feature, make this abandoned channel a candidate for inclusion in an AHZ (unless it has already been included in an HMZ).

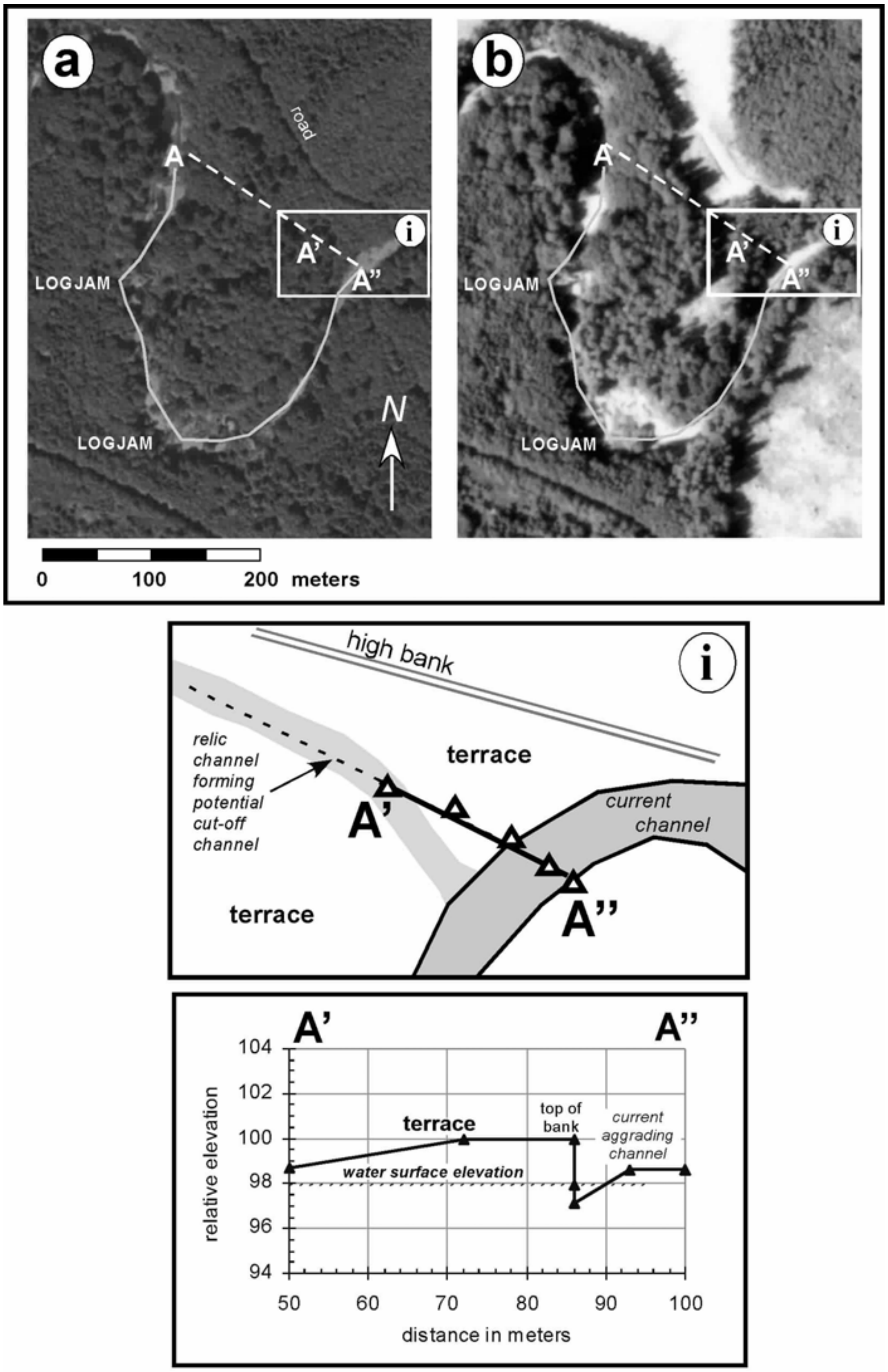

Figure 15. The Hoko River at location of the channel-spanning log jam in 1994 **(a)** and 2000 **(b)**. The channel width in **(b)** is significantly greater at the southern meander apex where the channel-spanning log jam formed. Likewise, vegetated islands are forming at this site. Both the log jam and channel width are continuing to increase, according to a field inspection conducted in 2002. Field mapping and hand level surveys also revealed a potential cut-off channel between the two meanders in **(b)** where an elevation difference exists between the active channel and the potential cut-off **(i)**. The potential cut-off occurs along a topographic low between the alluvial surface to the south (occupying the interior of the meander and about 4 ft higher) and the northern hillslope. Trees have also been cleared along most of the north side of the potential cut-off and part of its southern margin, which further places this site at risk of avulsion.

4.3 Delineating the Erosion Hazard Area

The EHA delineates the areas outside of the HMZ and AHZ which may be susceptible to bank erosion from (1) stream flow and/or (2) mass wasting that has been initiated by current fluvial processes and/or may be initiated in the future. When delineating the EHA, it is important for the analyst to keep in mind that an alluvial terrace bank with a vertical slope of unconsolidated material will become unstable when a river erodes its toe; also, an eroding vertical bank of unconsolidated material, whether it is a glacial terrace or a floodplain bank, is an active surface and consequently does not mark the edge of the CMZ. If the top of the bank is low enough, erosion may be limited to that which occurs solely from streamflow. However, when the top of bank exceeds the elevation of flood inundation (alluvial terraces), mass wasting processes can accelerate bank erosion (Thorne, 1999). This commonly occurs in incising streams as well as in streams that abut terraces composed of alluvium and glacial outwash (**Figure 16**).

Figure 16. An eroding terrace bank along the western margin of the lower Elwha River, looking upstream (July 2002). The terrace bank is composed of glacial outwash. Despite a height of ~41 m, the Elwha River actively erodes this bank and causes chronic mass wasting and instability. Because the river has sufficient transport capacity to remove all materials eroded from the bank, its vertical slope is maintained by the river's position along its toe. If the Elwha River migrates away from the toe of the terrace bank, a flatter slope angle will develop as mass wasting establishes a more stable configuration, thereby causing further retreat of the bank top.

Likewise, if the channel migrates away from the toe of an alluvial terrace bank, a flatter slope angle will develop as mass wasting establishes a more stable configuration, thereby causing even further retreat of the bank top. In other words, simply defining the erosion rate for a vertical terrace bank that is susceptible to mass wasting does not reflect the degree of erosion that will occur. For this reason, it is important to consider the geotechnical aspects of the slope in order to protect infrastructure from the geologic hazards posed by mass wasting that are initiated by channel processes. To this end, the analyst uses historical and field analyses to delineate the EHA, based on an estimated projected rate of erosion over the design life of the CMZ. In the instances where bank erosion occurs from mass wasting that has been initiated by fluvial processes, the EHA includes two components: the Erosion Setback (ES) and the Geotechnical Setback (GS) (**Figures 17** and **18**).

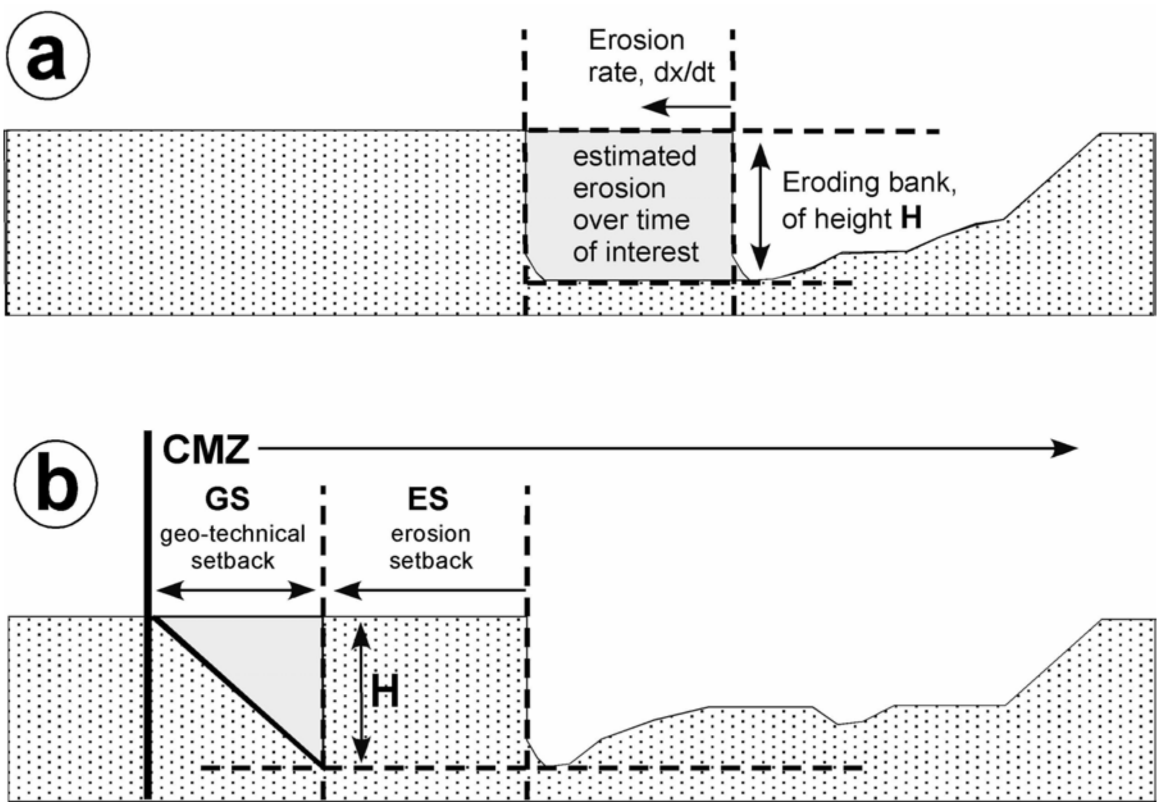

Figure 17. The ES is determined by estimating an erosion rate, dx/dt, for the design life of the CMZ **(a)**, and does not always begin along the active channel, but from the margins of the area that encloses the HMZ and/or the AHZ. The GS is intended to account for a vertical bank composed of erodible material that will adjust to a more stable configuration from mass wasting processes (slumping, landsliding, etc.) **(b)**, even if river erosion ceases (i.e., the channel moves away from the bank).

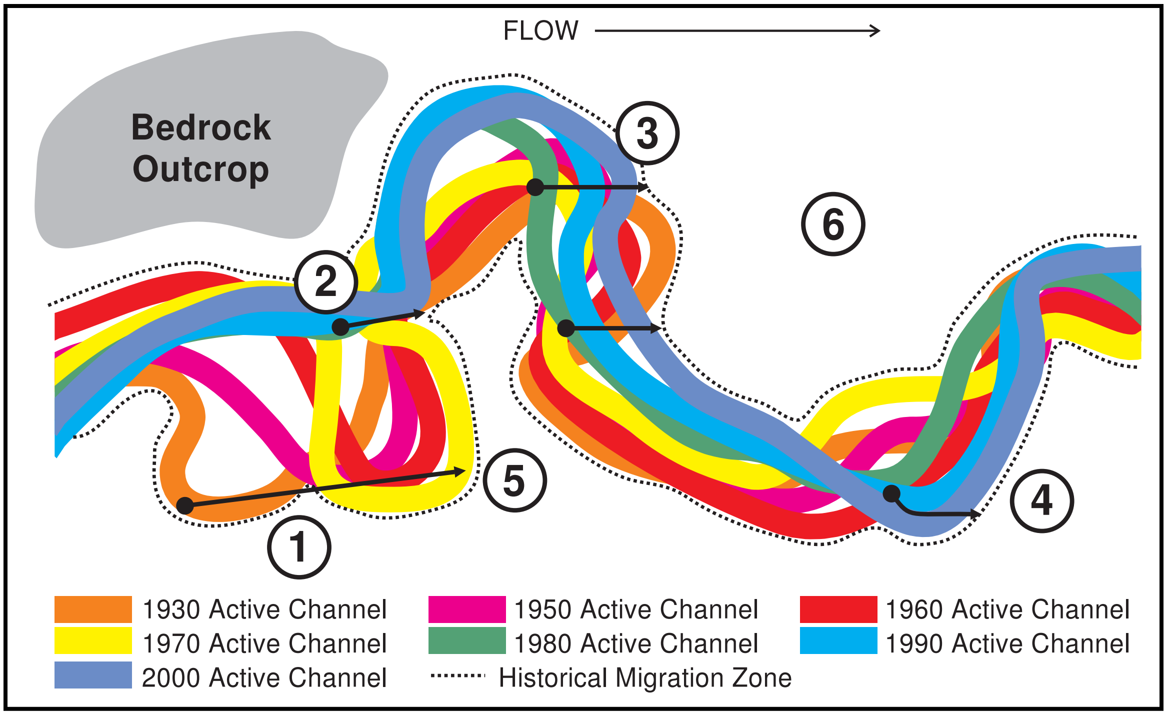

Figure 18. In this conceptual example, the EHA (ES + GS) includes the areas at risk of erosion based on the design life of the CMZ, trends in channel movement **(1)**, rates of channel migration, bank characteristics, bank erosion associated with AHZs **(2)**, and geologic constraints **(3)**. In this example, the meanders of the channel are generally trending in the downstream direction, and in many cases are currently eroding into the HMZ. The abandoned channels previously highlighted as avulsion hazards (**Figure 10**) will also experience channel migration if the main active channel occupies them. Accordingly, the EHA includes bank erosion occurring from AHZs as well as bank erosion associated with current trends in channel behavior.

4.3.1 Sources of Information

The analyst should supplement the following information with the appropriate field investigations:

- HMZ determination
- Trends in channel movement, rates in channel migration, and rates in floodplain turnover
- Geology maps: USGS and state resource agencies
- Field sheets (**Appendix B**)

For more information, refer to **Appendix D: Sources of Information**.

4.3.2 Determining the Erosion Setback

While the AHZ is based on estimates of bed aggradation and high discharge, the ES—as part of the EHA—accounts for floodplain and terrace banks that are too high in elevation to be at risk of avulsions, yet are still susceptible to channel erosion. Because channels can frequently change location, the ES is not determined solely by the current location of a channel (except in those cases where the channel currently extends or is anticipated to extend beyond the HMZ and/or the AHZ). Areas where the river may not necessarily have migrated in the historical record are therefore included in the ES because of the likelihood the river will migrate there in the future (within the design life of the CMZ). The extent of the ES is determined by using estimates of the rate of erosion that will occur over the design life of the CMZ.

The following method for estimating the ES can be automated in GIS by assigning values to individual pixels for bank conditions and rates of erosion (see **Appendix C**), a process similar to that outlined in Graf (2000).

The initial step for estimating the ES is to use historical studies to approximate floodplain turnover rates for each reach, as well as rates of erosion for banks with similar material properties, heights, and vegetation. (For procedures in calculating bank erosion rates and floodplain turnover rates, refer to **Section 4.2.2—Transect Measurements** and **Section—4.2.3 Polygon Analysis**.)

Next, the analyst assigns a percent of time the channel is likely to erode a particular location within the channel's valley bottom (C_E). The ES coefficient, C_E, can be estimated in a two-step process, beginning with the following equation:

$$C_E = E_R\left(\frac{T_E}{T_R}\right)$$

where E_R is the erosion rate of the bank material (determined from historical studies), T_R is the average time for the river to reoccupy the same location and T_E is the average time the channel is expected to erode at one location.

A channel can reoccupy the same position along its migration boundaries through two distinct mechanisms:1) progression of a meander bend downstream, and 2) channel migration back and forth across its valley bottom. Thus, T_R is estimated by taking the average between the time it takes a meander to move downstream one wavelength, T_{r1}, and the time it takes the channel to move across its valley bottom and back, $2T_{r2.}$ (The time it takes the channel to move from one side of its valley bottom to the other is $T_{r2.}$). Ergo:

$$T_R = \frac{(T_{r1} + 2T_{r2})}{2}$$

Consider the following example: If a river moves across its valley bottom every 150 years and its meanders move one wavelength every 100 years, then:

$$T_R = \frac{(100 + 2(150))}{2} = 200 \text{ years}$$

If the same river has eroded a terrace along the boundary of its valley bottom at a rate of 1.1 m per year for ten years before moving to a new location, then the erosion setback coefficient is:

$$C_E = 1.1 \, {}^{m}\!/_{yr} \left(\frac{10\,years}{200\,years} \right) = 0.055 \;\; m/yr$$

C_E is multiplied by the design life *(T)* of the CMZ (this example uses 500 years, but is ultimately determined by the analyst and/or local jurisdiction—see **Section 1.1**). Assuming T = 500 years, then:

$$E_S = T\,C_E = (500 \;\; yrs)(0.055 \;\; m/yr)$$

$$= 28 \;\; meters \;\; (rounding \;\; to \;\; nearest \;\; meter)$$

The limitations of this method are similar to Graf (2000) in that each pixel can potentially over or under represent bank erodibility depending on three factors: (1) the resolution and frequency of historical data used to estimate empirical rates of erosion, (2) the reliability of the field data that summarizes bank conditions (material properties, heights, vegetation), and (3) the timeline (*T*) used in the analysis. However, these factors apply to any method used for extrapolating areas at risk of future erosion, and this method has the substantial advantage of determining erosion risk independent of the current channel location. This is especially important as channel evolution in unstable systems is rarely linear; more often it is non-linear, episodic, and complex.

4.3.3 Determining the Geotechnical Setback

Once the ES has been delineated, a GS can be established to account for mass wasting that may occur at the ES boundary as the slope works towards achieving a more stable configuration by adopting a flatter slope angle. The GS is projected from the ES where it is estimated a vertical bank will form along the ES line. Since the channel edge is not expected to move beyond the ES line, the GS is placed where a stable slope configuration is predicted to occur (**Figure 11-b**). Generally, a GS determination is not necessary for vertical embankments composed of sound, well-indurated rock (such as a bedrock canyon), but it is potentially needed for vertical embankments composed of poorly indurated or fractured rock, and it is essential for embankments composed of unconsolidated materials (such as glacial outwash).

When evaluating the GS, the analyst should keep in mind that the stability of an alluvial channel or terrace bank that is prone to mass wasting is dependent on a number of factors, including:

- height of the ES bank
- composition of the bank material (geotechnical properties, structure, stratigraphy)
- vegetation
- land use

Site-specific evaluations are required because material and vegetative properties will vary from study reach to study reach. Accordingly, the analyst should be well-versed in bank stability modeling or find a qualified expert to complete this part of the CMZ delineation. Likewise, when estimating the GS, geotechnical properties the analyst should consider include: (1) shear strength (the internal resistance to shear stress that is the sum of internal frictional resistance and cohesion); (2) permeability of individual stratigraphic units; (3) interaction of these units; (4) type and age of vegetation; and (5) bank height.

See **Section 5.2—Bank Erosion and Slope Stability** for additional sources of information.

The GS can be determined from empirical field observations and/or from bank stability modeling. Although detailed explanations of bank stability modeling are beyond the scope of this report, excellent resources exist, such as the Bank Stability and Toe Erosion Model developed by the USDA National Sedimentation Laboratory (Dr. Andrew Simon and Dr. Eddy Langendoen), which is available free of charge at: http://www.sedlab.olemiss.edu/cwp_unit/bank.html.

To estimate the GS using empirical observations, the field sheets provided in **Section 4** and **Section 5** of **Appendix B** are useful for characterizing factors of fundamental importance to bank stability (Thorne, 1998). These field sheets include surveys for:

Bank Characteristics

- **Type**—for classifying the bank on the basis of its material properties (non-cohesive, cohesive, uniform, or layered).
- **Protection Status**—for noting whether or not the bank is stabilized by man-made revetments or structures.
- **Bank Materials**—for noting details of the composition of bank materials for up to four layers within the bank.
- **Layer Thickness**—for recording the thickness of each stratigraphic unit of the bank's composition.
- **Bank Profile Shape**—for augmenting the height and slope data by specifying the form of the bank profile.
- **Average Bank Height** and **Average Bank Slope**—for recording representative values for the overall height and steepness of the bank.

- **Tension Cracks**—for noting whether tension cracks are present behind the bankline.
- **Crack Depth**—for recording the depth of tension cracking as a proportion of the total bank height.

Bank-Face Vegetation

- **Vegetation**—for broadly classifying the types of vegetation found on the bank face.
- **Orientation**—for recording the angle at which the trunks of trees growing on the bank are leaning.
- **Tree Types**—for recording tree types (because deciduous and coniferous trees affect bank stability in different ways).
- **Tree Species**—for recording the particular species of any trees present.
- **Density and Spacing**—for describing the intensity and pattern of vegetative cover on the bank face.
- **Roots**—for defining the relationship between vegetation roots and bank surface.
- **Location**—for defining the position of vegetation on the bank profile.
- **Diversity**—for recording the mixture of vegetative types present on the bank.
- **Health**—for noting the state of the vegetation.
- **Age**—for evaluating the geomorphic history of the bank.
- **Height**—for determining the possible effect of vegetation in dragging down the bank and on impeding near-bank flow in the channel.
- **Lateral Extent**—for describing the width normal to the bankline of the band of bank vegetation.
- **Bank Profile Sketches**—for visually representing the bank in the study reach.

Geotechnical Failures

- **Failure Location**—for establishing the position of the failing area in relation to major channel features.
- **Present Status**—for establishing the condition of the bank at the time of observation.
- **Failure Scars and Blocks**—for noting the presence and appearance of two prominent features produced by bank instability.
- **Instability: Severity**—for putting any instability into perspective.
- **Instability: Extent**—for defining the scale of bank instability within the river system.

The analyst estimates stable slope configurations for different sets of conditions (material properties, heights, vegetation) by using empirical observations of stable slope configurations at analogous sites. This is a relatively straightforward approach when stable, vegetated slopes can be found within the study reach. (If stable, vegetated slopes are not present within the study reach, then bank stability modeling may be required.) The analyst can then use the height of the embankment, H, along with the estimated stable slope, S_h, to predict the GS:

$$\frac{\tan(90 - S_h)}{H} = GS$$

This method of estimating the GS should be verified against more accurate analytical models (e.g., the Bank Stability and Toe Erosion Model developed by the USDA National Sedimentation Laboratory, as noted above), particularly in cases where high embankments are currently eroding, or are at high risk of eroding in the near future. Additionally, the GS may need to be coordinated with a slope stability setback that has already been established by existing hazard area designations such as geologic hazard, steep slope, or landslide hazard regulations (e.g., in King County).

4.4 Delineating the Disconnected Migration Area

Human development has historically occurred on the low relief, productive land of river valleys and so the legacy of European settlement has led to the construction of thousands of miles of semi-permanent structures (e.g., earthen levees to provide flood protection and rock revetments to constrain rivers). The intent of DMAs is to indicate the impact of these structures by delineating the areas in which they prevent channel migration. DMAs provide a spatial context for the degree of human encroachment that has occurred within a CMZ, as well as how much aquatic and riparian habitat has been lost and how much of it could potentially be recovered. It is also important to distinguish DMAs from the CMZ in order to note areas that are undergoing development and are unprotected from channel erosion. These unprotected development areas represent substantial economic commitment in cases where they require future bank protection or where the local jurisdiction chooses to ensure that channel migration no longer poses a risk by purchasing property for conversion. Although it is possible to delineate DMAs relatively early in the CMZ study, the analyst should first delineate the CMZ without man-made constraints (unconstrained CMZ) (e.g., Perkins 1993, 1996), as this will provide the spatial context in which DMAs occur (constrained CMZ) (**Figure 19**). Another reason for delineating the DMAs at the end of the CMZ study is that it is very likely that efforts spent on determining the AHZ and EHA will have already covered much of the necessary office and field work.

In **Figure 19**, for example, a levee located at the upstream end of the reach confines the channel against a bedrock outcrop. Over time, this constriction may accelerate sediment deposition and channel migration downstream. Consequently, erosion may occur over greater areas in shorter time periods than what occurred prior to the inception of the levee. If accelerated erosion creates a greater demand for bank protection downstream of the current levee, the channel may become more confined, which will lead to more downstream channel instability.

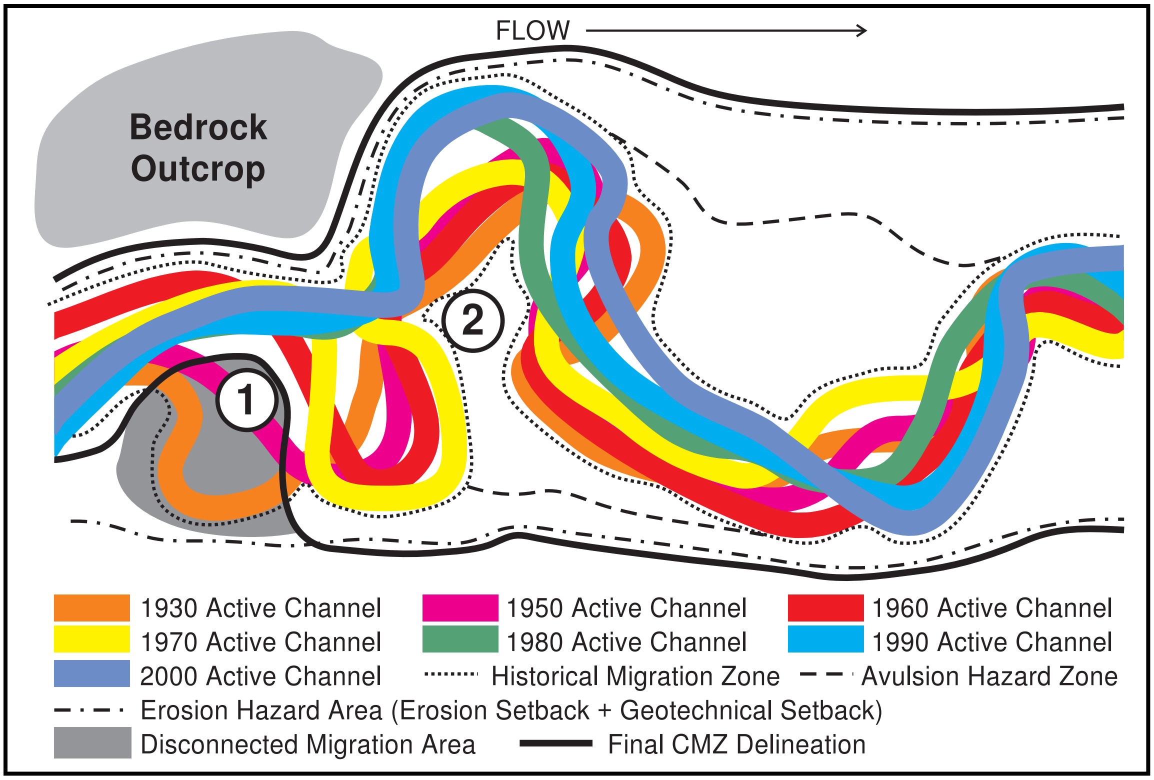

Figure 19. The DMA, the final component of CMZ delineation, takes into account the effects of man-made constraints (levees, revetments, railroads, etc.) that prevent channel migration into areas that would otherwise be at risk of erosion (EHAs). In this example, a levee located at **(1)** substantially confines the CMZ, which may result in more instability (accelerated channel migration and erosion) directly downstream **(2)**.

4.4.1 Sources of Information

The analyst should supplement the following information with the appropriate field investigations:

- Office and field observations from AHZ determination
- Office and field observations from EHA determination
- Aerial photographs
- Orthophotos
- State and County GIS resources: bank hardening and revetment GIS layer
- USGS topographic maps
- Field sheets (**Appendix B**)

For more information, refer to **Appendix D: Sources of Information**.

4.4.2 Surveying Man-Made Constraints

The analyst can make use of existing data (State and County GIS layers, aerial photographs, orthophotos, USGS topographic maps) to map the extent of railroads, roads, bridge abutments, levees, revetment (riprap) and other infrastructure that constrain channel migration. Discernment of man-made constraints on aerial photography depends on the visibility of the structure and resolution of the data. The analyst can then target for field inspection areas that appear to be hardened (e.g., portions of the alluvial channel that are narrow and deep and have not migrated over consecutive aerial photographs).

Next, the analyst can supplement existing data from the CMZ study with reconnaissance-level surveys to observe and record the extent and composition (type and average size of material used in structure) of bank hardening. There are field sheets in **Appendix B** for describing the extent and composition of bank hardening, as well as for coordinating field studies for other applications. Information provided in the field sheets include:

- **Levees** and **Levee Description**—for describing natural or man-made levees.
- **Levee Data** and **Levee Condition**—for recording levee height, side slope angle, and stability.
- **Width Control Types**—for defining the type of any width controls.
- **Width Control Frequency**—for identifying limits on the degree of widening and/or lateral migration by the local geology, floodplain alluvium, and/or man-made structures.

The analyst can then determine which structures constitute a legitimate barrier to channel migration: structures that are either semi-permanent (will endure beyond the design life of the CMZ), or structures that have public commitment to keep them intact (e.g., structures that protect populated areas, such as revetments and levees). Man-made structures with no public commitment for maintenance and structures made of erodible materials (sugar dikes) are not effective barriers to channel migration and are therefore not used to delineate a DMA.

Once the analyst has determined which structures constitute legitimate barriers to channel migration, the next step is to superimpose them on the unconstrained CMZ. This allows the analyst to delineate the areas of the channel's floodplain that are disconnected from the CMZ.

4.5 Delineating Relative Risk of Erosion Hazards

The risk of channel migration (and avulsion) is not equal within the entire mapped CMZ. Depending on the needs of the CMZ study, it may be necessary to approximate the relative risk of erosion hazards (**Figure 20**). The level of confidence in defining erosion risks is a function of the methods used for quantifying channel behavior, the quality of the data, and the degree of procedural and methodological error introduced in the study (see **Section 5.1**). Determinations of erosion hazard can be somewhat subjective, depending on the criteria the used for defining severe, high, moderate, and low risk. If probabilistic analysis has been completed for the study area (e.g., Graf 2000), then specific ranges of probabilities can be used to define severe, high, moderate, and low (i.e., 75-100%, 50-75%, 25-50%, 0-25%) probabilities of channel occupation.

Otherwise, the CMZ analyst relies on the following information for assessing relative risk:

- rates of channel migration, trends in channel movement, and floodplain turnover rates (**Section 4.1**)
- avulsion hazards (**Section 4.2**)
- erosion hazards (**Section 4.3**)
- locations of armored banks (**Section 4.4**)

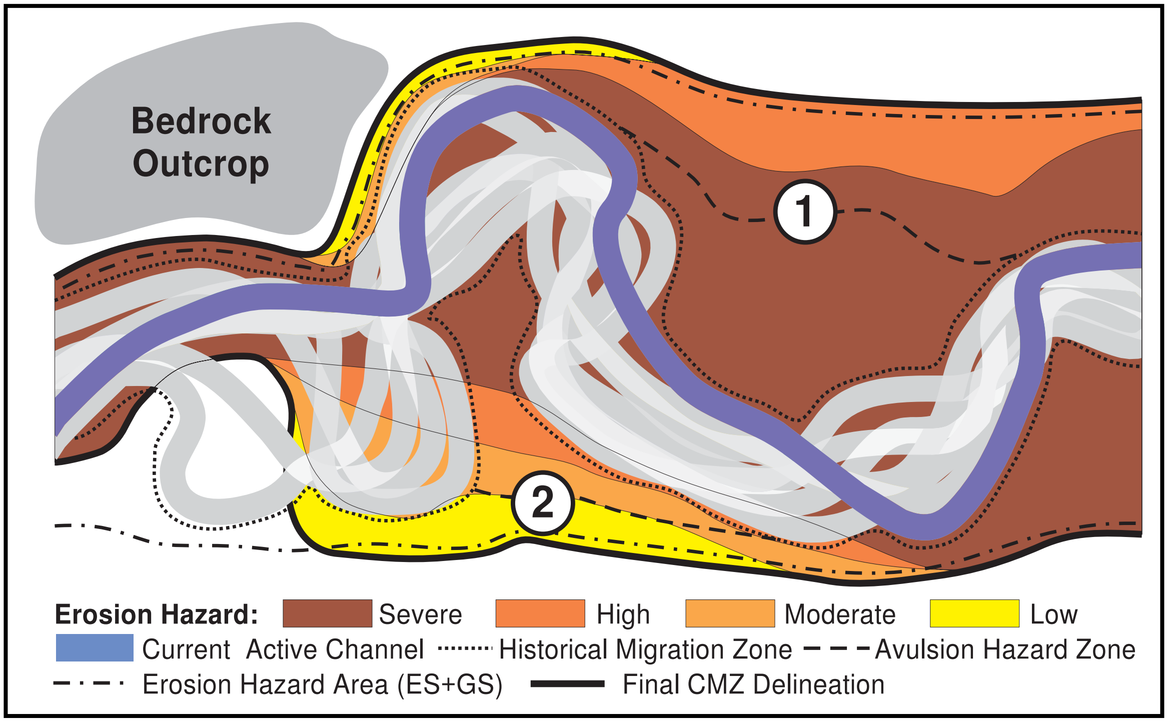

Figure 20. In this conceptual erosion hazard map, the current active channel is highlighted (blue) to illustrate how trends in channel movement make this river susceptible to erosion beyond its HMZ. Consequently, the areas downstream of the migrating channel are highlighted as a severe erosion hazard. Additionally, the AHZ identified as **(1)** is severely at risk in the event of a channel avulsion given its likelihood of occupation, which would be followed by lateral erosion. The other AHZ **(2)** is considered a moderate erosion hazard because it is less likely to be occupied by the main channel.

Given erosion hazard determinations may rely substantially on best professional judgment, it is especially important that only qualified individuals extensively trained in geomorphology make these calls. Additionally, the analyst should clearly explain how particular levels of hazard (low, moderate, high, severe) were determined and their consistency with pertinent regulations, especially as they relate to anticipating future channel change.

5 Summary

The principal goal of CMZ delineation is to predict the area of a river system that is at risk of future channel erosion due to fluvial processes. The purpose of this report, therefore, is to provide the framework for evaluating how trends in channel movement, changes in boundary conditions, and the context of a channel's disturbance history contribute to future channel behavior. To that end, four components are identified—the HMZ, AHZ, EHA (ES + GS), and DMA—that collectively make up the CMZ; three of these—the AHZ, EHA, and DMA—have varying degrees of relevancy, depending on the river system in question. How precise and accurate the determination of any of these components depends on the level of integrity of the historical and field analyses.

Before a CMZ study begins, a design life (how long into the future the CMZ is intended to account for channel processes) must be established. As previously stated, the funding agency (city, county, and/or state) will usually already have determined the design life of the CMZ (along with other information that pertain to regulatory statutes). In those instances where it has not already been determined, or the aims of the study do not correspond to compliance with local ordinances, the design life should be far-reaching enough to account for long-term alterations of the fluvial landscape.

As reported in greater detail in **Section 4.2,** in order to understand the first component—the HMZ—the analyst first maps the extent of the locations of the channel over time, identifies trends in channel movement (channel migration and avulsion) that extend beyond the HMZ, calculates rates of erosion over the CMZ design life, and calculates floodplain turnover rates for each reach. **Figure 6** illustrates why further analysis is required to determine if avulsion hazards exist beyond an HMZ, depending on vegetation, topography, and factors that may cause aggradation of the channel bed (e.g., log jams and snags).

The next component—the AHZ (**Section 4.3**)—accounts for any avulsion hazards that may extend beyond the HMZ, and is determined by: (1) empirical observations of bank stratigraphy and the role of LWD in channel bed dynamics; (2) vegetative characteristics; (3) topography and elevation of fluvial features; (4) survey data; and (5) hydraulic modeling (**Figure 10**).

The third component—the EHA **(Section 4.4)**—delineates the areas outside of the HMZ and the AHZ that are at risk of channel erosion (either from stream flow and/or mass wasting) over the design life of the CMZ; the EHA includes bank erosion anticipated from the AHZ, as well as bank erosion associated with current trends in channel behavior (**Figure 18**). The EHA's two components—the ES and the GS—account for bank erosion that occurs along floodplain and terrace banks that are composed of erodible materials (outwash, alluvium, loess, floodplain sediments). The ES (**Section 4.3.2**) is determined from rates of erosion and floodplain turnover rates for banks composed of similar geologic materials, heights, and vegetative characteristics. For slopes prone to mass wasting (due to current and/or anticipated erosion of the toe from channel processes), the

GS (**Section 4.3.3**) establishes a stable slope beyond the ES in anticipation of a stable angle of repose.

The DMA is the fourth and last component, given that the field survey of bank protection is best coordinated with the other field studies that precede it. In other words, much of the information the analyst will need to delineate the DMA will already have been acquired in the process of determining the HMZ, AHZ, and EHA. The purpose of delineating a DMA is to determine the impact of man-made structures (such as levees, revetments, roads, and railroads) on channel migration and also to determine the possible impact of future channel migration on public and/or private developments and property.

The culmination of these efforts also allows the analyst to determine the relative risk of erosion hazards (**Section 4.5**). In the instances where probabilistic methods are used to evaluate channel movement over time, the analyst can define and map hazards by percent ranges (e.g., 100-75%, 75-50%, 50-25%, 25-0%). This approach, of course, has its limitations and should only be applied in rivers where the HMZ captures the full extent of anticipated future channel behavior. Otherwise, the analyst must rely on information that provides rates of erosion, trends in channel movement, avulsion hazards, erosion hazards, and locations of bank protection to evaluate relative risk (**Figure 20**). Reliance on best professional judgment emphasizes the need for qualified professionals (extensively trained in geomorphology) to make these calls.

5.1 Evaluating the Reliability of the CMZ Study

Every CMZ study should evaluate the quality of the field-based and office-based work products by thoroughly examining where procedural and design flaws corrupt the CMZ determination or diminish its reliability. All potential sources of error should be discussed in the CMZ report.

Notably, all of the issues described below become insolvable only if they are not discovered in time. To that end, the following list provides a basis for evaluating the level of confidence of the CMZ study (Reid 2001). All office products and field collection schemes should be evaluated for data quality and procedural errors.

Sources of Design Flaws

- Method cannot measure what is needed—sampling plan is unable to provide the kind of information that is needed to meet the study's objectives.
- Study too short—the study is of insufficient duration to answer the key questions of the study.
- Inadequate problem analysis—collecting data that is irrelevant to the problem the study is intended to address.
- Fundamental misunderstanding of system—physical and biological systems do not always work as assumed.
- Statistically weak design—lack of efficiency stemming from lack of attention to statistical requirements of the study.

Sources of Procedural Flaws

- Less than ideal field workers—personnel that lack training or lack motivation.
- Data not worked up in time—analysis of the data does not occur in time to know if there is a problem.
- Collateral information missing—lack of collateral information needed to interpret results, such as whether measurements were in feet or meters, or the date of a benchmark change was not written down.
- Cryptic technology—occurs in context of rapid increase in data loggers, GIS, LiDAR, global positioning systems, and other sophisticated tools that are not fully understood by those using them.
- Personnel change—lack of continuity in the process (e.g., the original project manager is promoted and the field work is given to other personnel who do not give it priority or do not have the proper professional and academic background to complete the work.
- Lack of institutional commitment—the study is under-funded.
- Protocol changes prevent comparison—updated field techniques make comparison to older data impossible.

5.2 Sources for Additional Information

Historical Studies/Aerial Photographic Interpretations

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Glossary

accretion. The gradual addition of land along the edges of a channel by lateral migration (which deposits sediment carried by stream flow).

active channel. The portion of a channel that is largely unvegetated, at least for some portion of the year, and inundated at times of high discharge (Montgomery and MacDonald 2002).

aggradation. An increase in sediment supply and/or decrease in sediment transport capacity that leads to an increase in the channel bed elevation. An increase in base level can decrease sediment transport capacity, thereby initiating aggradation.

alluvial channel. A channel formed in material (sand, gravel, cobbles, or small boulders) that moves during floods. Alluvial channels convey channel bed and bank materials under present flow conditions and adjust their dimensions, shape, and gradient under the present hydrologic regime. For the most part, streamflow, sediment supply, and woody debris control how alluvial channels change over time.

alluvial fan. A fan-shaped deposit of alluvium laid down by a stream that emerged from an upland into less steeply sloping terrain.

alluvial terrace. An abandoned floodplain, produced by past vertical instability in the fluvial system. Alluvial terraces are inactive depositional surfaces within a current hydrologic, climatic, and tectonic setting. Alluvial terraces can result from a lowering of the river's base level, from channel incision, or from changes in hydrology.

alluvium. Material (sand, gravel, cobbles, or small boulders) that is deposited by flowing water.

anastomosing channel. A type of alluvial channel with multiple, interconnected, coexisting channels. Anastomosing channels have vegetated islands between channels, whereas braided channels have bare bars. Two processes occur simultaneously in anastomosing channels: (1) avulsion, which creates a pattern of multiple channels; and (2) lateral migration of the individual channels that exist within the anastomosing pattern (i.e., individual meander belts).

avulsion. Described by Allen (1965 5:119) as "the sudden abandonment of a part or the whole of a meander belt by a stream for some new course." Channels may avulse into an abandoned channel or create a new channel depending on the preexisting boundary conditions that initiate the avulsion.

Avulsion Hazard Zone (AHZ). The portion of the CMZ that delineates avulsion hazards not accounted for in the HMZ.

bankfull stage. The stream level that corresponds to the discharge at which channel activity (sediment transport, the formation and/or reformation of bars, the formation and/or alteration of bends and meanders, etc.) results in the normally occurring morphologic characteristics of channel (Dunne and Leopold 1978).

base level. The elevation of the receiving water body (which controls the ultimate elevation of the stream).

bedload. The portion of the total sediment load that slides and rolls along the channel bed as a layer of randomly colliding particles. Bedload typically includes sand, gravels, cobbles, and boulders.

channel confinement. The width of the channel's valley walls relative to the width of the bankfull channel. Used to describe how much a channel can potentially shift within its valley.

channelization. The artificial straightening and deepening of a stream channel to induce faster flow, to reduce flood occurrences, or to drain marshy acreage for farming.

channel migration. A change in the location of a stream or river channel due to bank erosion or avulsion.

channel network. The drainage system of channels that convey surface water, subsurface flow, sediment, and organic matter.

channel reach. A specific portion of the length of a channel that has similar physical features, such as gradient and confinement.

clast. An individual constituent, grain, or fragment of rock, produced from the breakdown of a larger rock or mass.

colluvium. Angular sediment deposits found at the base of hillslopes; the product of gravity-driven mass movement from hillslope erosion.

cut-off avulsion. A type of avulsion that bisects the neck of a meander and connects the apex of one meander with another downstream. Cut-off avulsions leave behind an abandoned oxbow channel or lake.

dam-break flood. Downstream surge of water caused by the sudden breaching of an impoundment in a stream channel; a form of a debris torrent. The rapid failure of the dam (formed by a landslide, the deposit of a debris flow, or a woody debris jam) can cause up to two orders of magnitude larger than normal storm-runoff floods. These extreme hyper-concentrated (water > sediment) floods can occur in 1st through 6th order streams, in both natural and managed landscapes.

degradation. Incision, or down-cutting of the channel bed.

Disconnected Migration Area (DMA). The portion of the CMZ where the channel has been physically disconnected from its CMZ by man-made constraints.

ephemeral channel. A channel that only flows during or immediately after a rainfall.

Erosion Hazard Area (EHA). The area of the CMZ unaccounted for in the AHZ or the HMZ that delineates channel susceptibility to bank erosion from stream flow or mass wasting. The EHA is defined by the ES and the GS.

Erosion Setback (ES). As part of the EHA, the ES encompasses the area outside the HMZ and AHZ that is susceptible to channel erosion; it includes those areas that are not at risk of avulsions, but are susceptible to stream or river erosion.

facies. The aspect, appearance, and/or characteristics of a rock unit that reflect the conditions of its origin and that differentiate it from adjacent or associated units.

failure. A mass wasting event where a bank hillslope's face destabilizes and moves downslope.

fluvial. Of, happening in, belonging to, produced by the action of, or pertaining to a river.

Froude number. The ratio of inertial to gravitational forces; determines if a flow is subcritical (slow or tranquil) or supercritical (fast or rapid):

$$Fr = \frac{u}{\sqrt{gh}}$$

where Fr = Froude number; u = the mean velocity; g = the acceleration due to gravity; and h = the flow depth. When $Fr < 1$, flow is subcritical; when $Fr = 1$, flow is critical; and when $Fr > 1$, flow is supercritical.

functional wood. The stable accumulation of wood that is large enough to influence flow and sedimentation; develops from recruitment of key members (individual pieces of wood that are likely to be stable within the channel.

geomorphology. The branch of geology and geography which deals with the form of the earth, the general configuration of its surface, and the changes that take place in the evolution of land forms.

Geotechnical Setback (GS). As part of the EHA, the GS extends from the outer boundary of the ES for the purpose of establishing a stable slope configuration following mass wasting. GS delineation accounts for the natural adjustment process that an embankment over-steepened by channel erosion will go through.

Historical Migration Zone (HMZ). The portion of the CMZ study area that the channel occupied in the historical record.

imbrication. The shingle-like deposition of relatively flat gravel or cobbles over one another. Imbricated grains are inclined: the lower end points upstream and is overlain by the next incoming grain.

impoundment. A fluvial feature that is large enough to decrease channel flow velocity and initiate sedimentation.

incision. A decrease in sediment supply and/or increase in sediment transport capacity that leads to a decrease in the channel bed elevation. A decrease in base level can cause headcutting that migrates upstream, thereby initiating aggradation downstream.

indurated layer. A soil layer that has become hardened, generally by cementation or compaction of soil particles.

key member. An individual piece of wood that is large enough to become stable within the channel.

low-flow channel. The wetted channel during periods of low precipitation, usually late summer and early fall.

Manning's equation. A formula The Manning's equation is typically used for estimating discharge for steady uniform flow:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

where Q = discharge; n = Manning's n; A = cross-sectional area of the flow; R = hydraulic radius, and S = slope. Manning's n is a composite factor that accounts for the effects of many forms of flow resistance, such as channel roughness from vegetation, channel bed forms, sediment characteristics, and flow depth.

mass wasting. The downslope movement of material due to gravity (rather than water, wind, or ice, for example).

montaine. Of or pertaining to mountains.

moraine. An accumulation of earth, usually with stones, transported and finally deposited by a glacier.

overbank deposition. Material deposited on the floodplain during high flow events; typically include sand, silt, clay, and wood.

perennial streams. Streams that flow year-round.

planform. The shape and size of channel and overbank features as viewed from above.

relic channel. An abandoned channel that is not presently active.

secondary channel. Any channel in the study area besides the main channel; examples of secondary channels include side channels, abandoned channels, swales, overflow channels, and relic channels.

shear strength. The internal resistance to shear stress that is the sum of internal frictional resistance and cohesion.

shear stress. Stress caused by forces operating parallel to each other but in opposite directions.

shingle. Gravel that consists solely of large smooth pebbles (without finer material).

strath terrace. a bedrock terrace that was formed by rock uplift.

stream power. The amount of work (material transportation) a channel reach can accomplish, measured by flow per unit of time, where work and energy have the same units. Stream power has a number of definitions depending on the time rate at which either work is done or energy is expended. It is a useful index for describing the erosive capacity of streams, and relates to channel pattern, development of bed forms, sediment transport, and the shape of the longitudinal profile.

study reach. The portion of the channel that is within the study area.

supply-limited. Describes a channel with sufficient power to continue movement of the majority of materials that enter the channel reach. Steep, bedrock channels are supply-limited.

swale. A vegetated ephemeral channel that may or may not correspond to a relic channel.

thalweg. The line that defines the deepest part of a channel.

till. Unstratified glacial drift that was deposited directly by the ice; consists of intermingled clay, sand, gravel, and/or boulders in any proportion.

transport-limited. Describes a channel that tends to store a portion of the materials that enter its reach for some period of time. Channels with floodplains are transport-limited.

unconsolidated material. Sediment that is loosely arranged, unstratified, or not cemented together; can occur at the surface of a channel or at depth.

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Appendix A: Channel Patterns And Types Of Channel Movement

A.1 Channel Patterns

Braided Channels

Braided streams or channels consist of two or more low-flow channels divided by bars that become inundated at bankfull stage (**Figure A-1**) and are subject to frequent shifts in channel position. Knighton (1998) describes four conditions that favor the development of braided channels: abundant bed load (high sediment supply), erodible banks, variable discharge, and relatively high stream power. The bankfull braided channel can be identified by a more or less straight alignment (low sinuosity), although individual low-flow channels may be more sinuous. Additionally, distinctive topographic levels can be identified across the braided channel area, ranging from the most active channels to elevated, abandoned areas, the latter of which may become reoccupied and enlarged during high discharges (when rapid shifts in channel position are common) or when the active channel aggrades above relic channels.

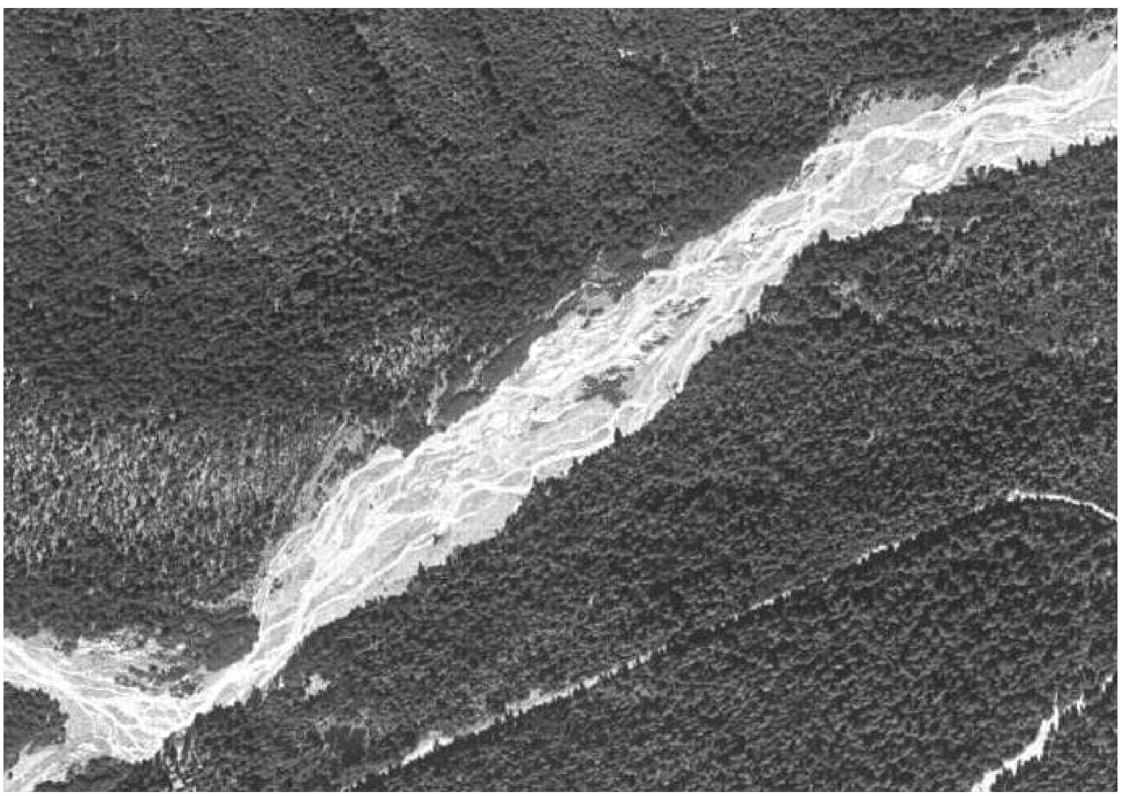

Figure A-1. A braided channel: Upper White River in Mount Rainier National Park, WA. At bankfull flow this reach would look like a single channel since all the unvegetated bars would be submerged. Aerial photo 1994.

Meandering Channels

It is widely believed that the relative scarcity of straight channels indicates that meandering is the natural state of most single threaded channels. Meandering channels (**Figure A-2; Figure A-3**) adjust according to their width-to-depth ratios: wide, shallow channels tend to have a lower sinuosity than narrow, deep ones. Chitale (1973) shows how the width-to-depth ratio of a channel can influence the distribution of erosion in meander bends, and therefore their stability and how they travel across the landscape. For instance, Chitale asserts that because bank erosion in narrow, deep channels is concentrated at the apex of the meander bend, it causes sinuosity to increase until eventually a cut-off develops across the narrowed neck. In wide, shallow channels, on the other hand, where erosion is concentrated downstream of the meander apex, meanders tend to travel downstream instead of developing a cut-off (Knighton 1998). Additionally, meandering also occurs from local variations in erosional resistance of the bed and bank material (Mount 1995): increased bank roughness tends to diminish rates of erosion and concentrates erosion at the apex of the meander, while reduced bank roughness tends to increase rates of erosion and concentrate erosion downstream of the meander apex (Furbish 1991; Thorne and Furbish 1995).

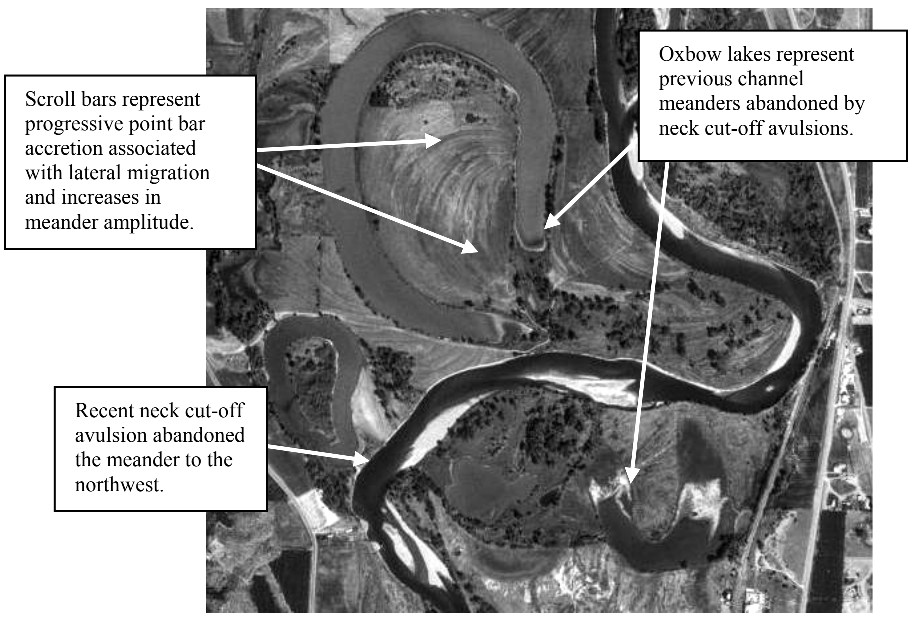

Figure A-2. A meandering alluvial channel: Okanogan River, near Oroville, WA. Aerial photo 1995.

Not all meandering rivers migrate, however. Some meander patterns can remain stable for hundreds, even thousands of years (e.g., Alexander and Nunnally 1972). Deeply entrenched bedrock canyons, for example, can present a meandering channel planform, and although tidal slough channels have high sinuosity values, they do not tend to migrate (Leopold et al. 1993; Collins et al. 1986) due to the stabilizing effects of vegetation and cohesive sediments.

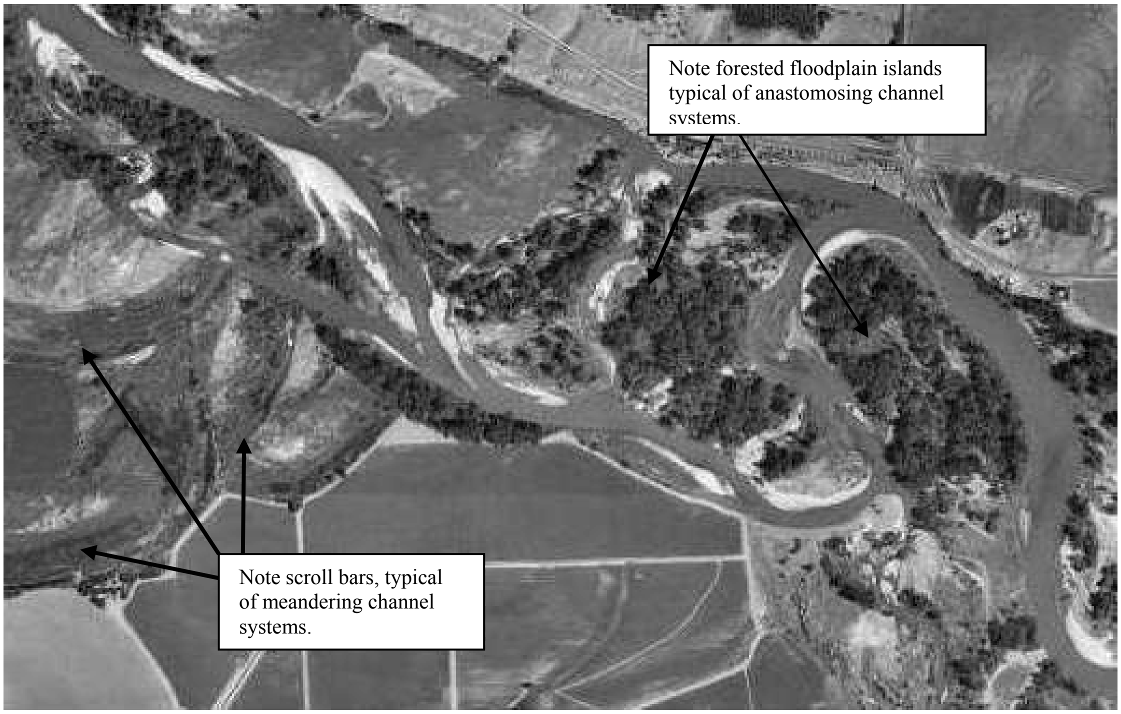

Figure A-3. With scroll bars and forested floodplain islands, this reach has the characteristics of both meandering and anastomosing channels. Yakima River, near Toppenish, WA. Aerial photo 1996.

Anastomosing Channels

The anastomosing channel pattern typically presents a river with multiple, interconnected, coexisting channels on an alluvial plain (**Figure A-4**). Two processes occur simultaneously in anastomosing channels: (1) avulsion, which creates a pattern of multiple channels, and (2) lateral migration of the individual channels that exist within the anastomosing pattern (i.e., the development of individual meander belts). Each channel within an anastomosing river has a meander belt, or zone of fluvial activity, meaning the anastomosing river has multiple, coexisting meander belts. Anastomosing channel systems tend to occupy the entire valley bottom and are susceptible to significant vertical change over relatively short time frames (Abbe 2000; Makaske 2001).

Although anastomosing channels can be confused with braided channels because they look similar at low-flow, the two types of channels are easily distinguished by several significant differences: (1) in an anastomosing system, avulsion cuts a new channel or reoccupies an existing channel within a vegetated floodplain, while in a braided system, large pulses of sediment deposit within the active channel itself, which causes the channel to widen and to occupy numerous channels that repeatedly diverge and converge; (2) unlike braided rivers, the individual channels within an anastomosing reach tend to be laterally stable; (3) the relative elevation of anastomosing islands is typically above bankfull stage, whereas bars in a braided channel are typically below the bankfull stage, which means that (4) an anastomosing reach retains its multi-channeled appearance at bankfull stage, whereas the number of channels in a braided reach diminish; and (5) the islands in anastomosing channels are vegetated and generally larger than the bare or lightly vegetated bars found in braided channels (Smith and Putnam 1980; Knighton and Nanson 1993; Makaske 2001).

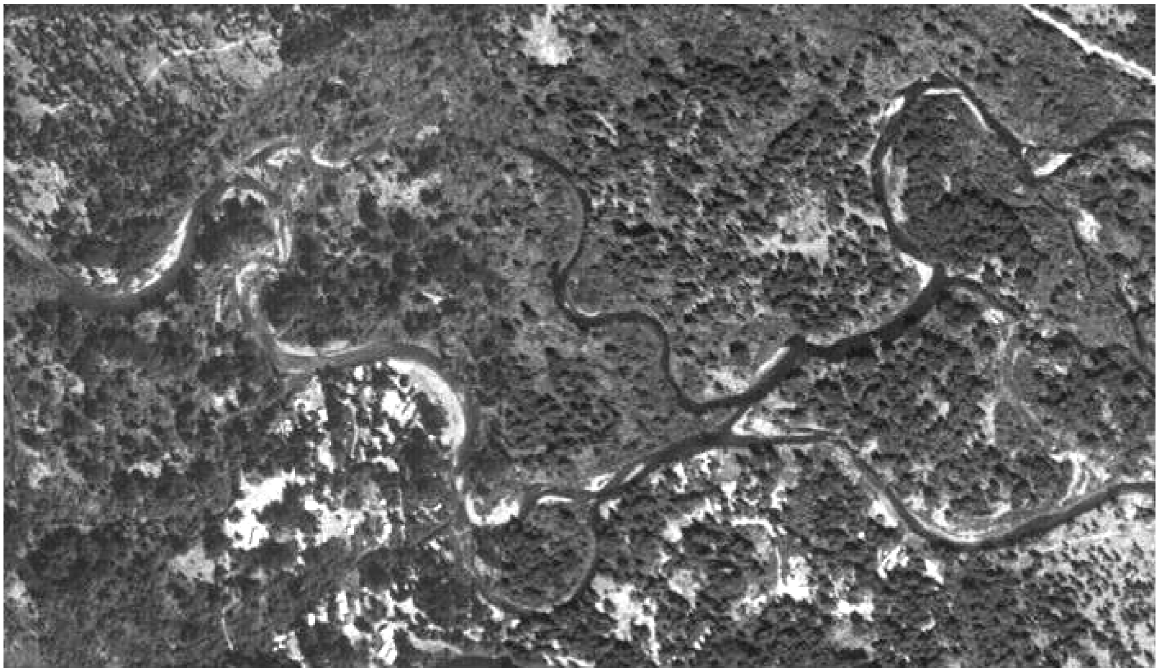

Figure A-4. An anastomosing channel: Yakima River, near Easton, WA. Unlike a braided channel, during bankfull flow the multiple channels in this system will still be clearly visible. Aerial photo 1998.

Root cohesion from vegetation is one of several factors that plays an important role in the stability of anastomosing channels. Low stream power and cohesion of bank material in low-gradient anastomosing systems also increase lateral stability. Or looked at another way, low floodplain gradients favor channel avulsion and split flows between multiple channels, which diminishes stream power that would otherwise accelerate channel bank erosion (Makaske 2001). This means that local flow diversion associated with woody debris loading can influence development of an anastomosing channel. (Harwood and Brown 1990; Abbe and Montgomery 1996; Collins and Montgomery 2002).

Bedrock Channels

While meandering, braided, and anastomosing rivers occupy an alluvial valley larger than the channel itself, bedrock channels are predominantly controlled by their geological environment: flow is confined between rock outcrops and channel morphology is determined by the relative strength and weakness of the bedrock material (Gordon et al. 1992). Bedrock channels are formed in areas of active rock uplift and over time incise deep canyons (Mount 1995). Because down cutting is rapid, these channels establish relatively narrow and localized alluvial plains which are separated by long stretches where the river is confined primarily to a gorge. Even though bedrock reaches can have very steep gradients, high stream power, and high sediment loads, they may be straight or sinuous (**Figure A-5**), depending on how they were formed. Regardless, CMZs along this channel type typically follow the bedrock exposure bordering the channel.

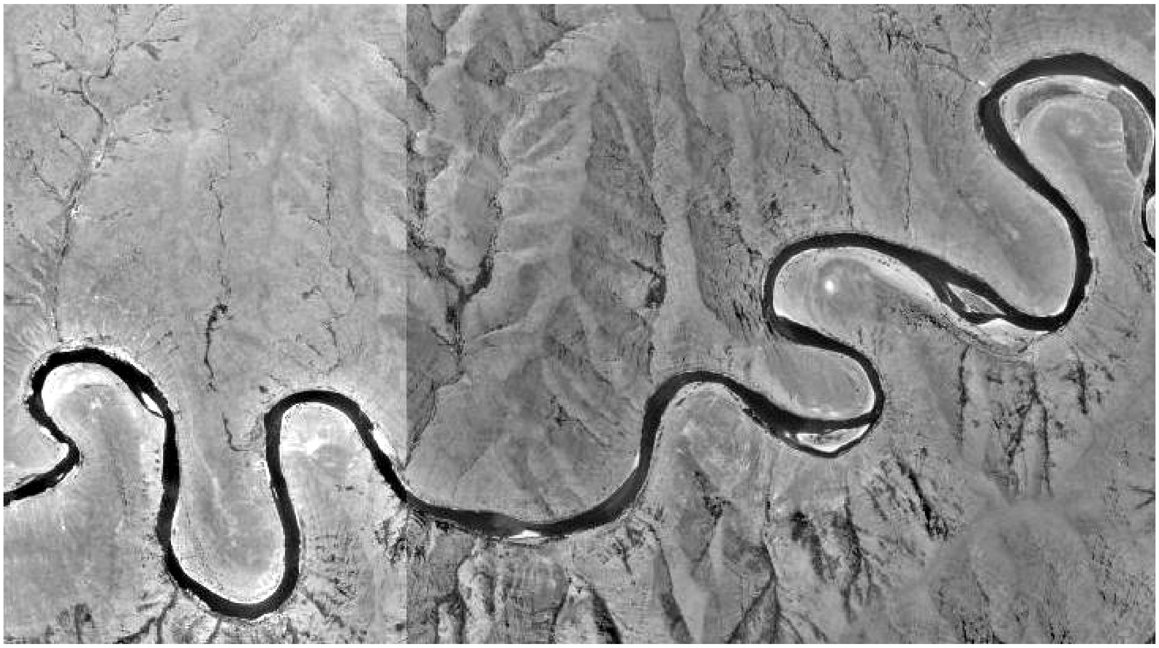

Figure A-5. A sinuous entrenched bedrock channel: Grande Ronde River, near Clarkston, WA. Aerial photo 1996.

Bedrock channels are supply-limited, which means they typically have sufficient sediment transport capacity to convey whatever materials are delivered to the reach. The overall channel pattern of these upland rivers should be considered separately from lowland streams: upland rivers are much more influenced by geological environment, as well as rate of uplift and associated rate of incision (Mount 1995), than by flow strength, bank erosivity, and sediment supply.

Distributary Channels

Distributary channels occur in environments where a river or stream experiences a drop in gradient and branches into more than one channel. Two examples of distributary channels include deltas and alluvial fans.

Deltaic Channels

Deltas comprise the most downstream end of a channel network, and consist of broad, low-lying alluvial land that is subject to frequent inundation. Deltas can occur in both fresh and marine waters: they form where streams and rivers enter a standing body of water, such as a lake, reservoir, sound, or bay. Deltas are formed when a channel enters a standing body of water: the channel's energy gradient approaches zero which causes it to slow down, drop its sediment load, and aggrade; aggradation causes avulsions which in turn create a distributary channel network that delivers sediment to low-lying floodplains in a fan-like complex (**Figure A-6**). This process is somewhat analogous to that of alluvial fans, except that deltas are relatively flat, while alluvial fans are relatively steep.

Figure A-6. A highly altered deltaic distributary channel; Snohomish River, Everett, WA. Aerial photo 1990.

By virtue of the way they are formed, deltas are transport-limited—or response—environments, and therefore retain large quantities of sediment. Delta evolution is dependent on long-term changes in base level (the water elevation of the water body in which the river enters), woody debris, and sediment supply. Long-term change in any of these conditions will influence the rate at which the delta grows. Deltas are also particularly susceptible to ground subsidence where levees diminish or eliminate overbank deposition. The CMZ typically encompasses the entire delta.

Alluvial Fans

One of the most dynamic landforms in the channel network, alluvial fans occur where steep, confined channels emerge into unconfined, low-gradient channels, or broad flat areas (**Figure A-7**). When a tributary abruptly enters a larger valley in this fashion, it experiences a dramatic decrease in its sediment transport capacity which results in rapid deposition of bed material. Due to this sudden drop in transport capacity, many alluvial fans have braided channels across their surface: as the emergent channel aggrades it becomes distributary (similar in planform to a delta), finds lower routes, and then abandons its previous channel. This process repeats itself in discrete avulsion events, and ultimately builds an arcuate—or fan-shaped—landform, its upper apex at the junction where the tributary enters the valley. Unless the channel is no longer active within the hydrologic, climatic, and tectonic regime, the CMZ encompasses the entire area of the alluvial fan.

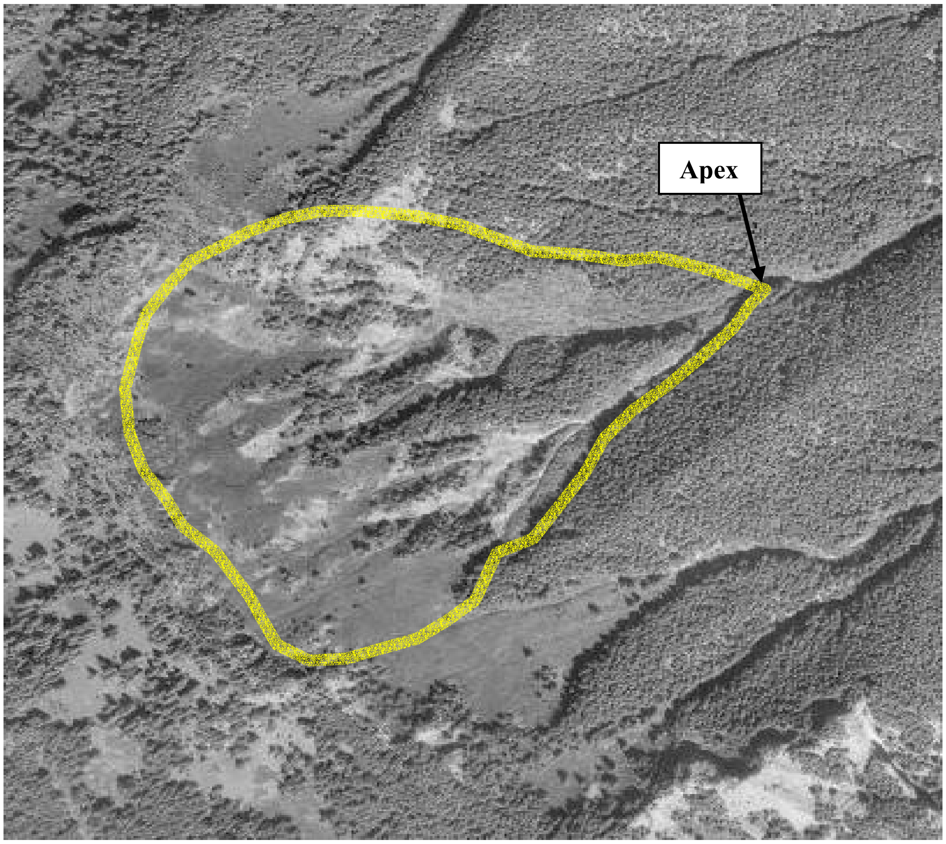

Figure A-7. An active alluvial fan, near Packwood, WA. As bedload rapidly accumulates, the channel aggrades and moves to a lower location. This process creates a fan-like landform composed almost entirely of bed material. Note the CMZ of this fan begins where the stream first splits into two channels. In this example, stream flow is ephemeral across the lower portion of the fan. One of the most dynamic areas within any landscape, alluvial fan CMZs pose substantial risks and costs if developed. Aerial photo 1993.

A.2 Types of Channel Movement

How channels respond to hydrologic, sedimentologic, and organic inputs influences the development of channel patterns described in **Section A.1.** Channels respond with horizontal movement and/or vertical movement to perturbations in streamflow, sediment supply, bank erodibility, vegetation, and/or woody debris. While stable or equilibrium conditions are the norm in non-alluvial (bedrock) channels, they are rare in alluvial channels; when they do occur it is typically due to the stabilizing influence of vegetation on bank materials.

Horizontal Movement

Horizontal channel movement (lateral migration, avulsion, widening, narrowing) involves the erosion of a preexisting floodplain or terrace and can pose a direct threat to development in areas susceptible to such erosion. Large rivers are more prone to significant horizontal shifts in channel location than are smaller channels.

Lateral Migration

Lateral migration generally occurs as the result of one of three processes: meander bend development, channel response to a flow obstruction that initiates bank erosion on the opposing bank, or an increase in bank erodibility (as occurs following removal of vegetation).

In meander bend development, the curvature of the bend accelerates flow—and therefore erosion—around the outer edge of the bend, and decelerates flow on the inside, which causes the inside of the bend (the point bar) to accumulate sediment, which further concentrates flow around the outer edge of the bend, and so on. Because erosion around the outer edge of a meander is generally counterbalanced in this fashion with deposition on the point bar, the channel's hydraulic geometry remains relatively constant during lateral migration (Mount 1995).

Lateral migration also occurs where an obstruction or discontinuities in bank conditions (such as changes in roughness or cohesion) deflect flow into an erodible bank, thereby causing the channel to relocate (Church 1992). Two examples: (1) when large trees fall into the channel they can redirect flow into the bank and thereby accelerate bank erosion; and (2) log jams can accelerate erosion by increasing channel curvature around meanders (Trimble 1997, Abbe and Montgomery in press).

Avulsion

Avulsion refers to "the sudden abandonment of a part or the whole of a meander belt by a stream for some new course…" (Allen 1965, 5:119). Avulsions can cause rapid, dramatic shifts in channel location from one side of a valley bottom to the other within a single flood event. Channels may avulse into an abandoned channel or create a new channel depending on the preexisting boundary conditions that initiate the avulsion. Conditions that favor avulsion include aggradation of the floodplain and rapid in-channel deposition that raises the streambed elevation. For example, a trigger, such as a major flood event or an obstruction (beaver dams, log jams, ice jams, dunes), can elevate water levels and initiate the avulsion process (Makaske 2001). Timber harvest of floodplains can also trigger avulsions by decreasing erosion resistance of flood waters.

Cutoffs are a type of avulsion that take place in meandering streams. Cutoff avulsions increase channel gradient and local transport capacity in response to excessive sinuosity that has become unable to transport its sediment load (Knighton 1998). As a meander bend increases in amplitude, the channel attains a sinuosity it can no longer maintain and cuts the bend off. Cutoffs that occur on tortuous meanders through the shortest path where two apexes come together are known as neck cutoffs. Chute cutoffs, on the other hand, are generally more common since they occur across point bar or floodplain deposits of low elevation. In-stream structures, such as log jams, can increase the probability of cutoff channels by initiating channel aggradation and raising water surface elevations.

Widening
Channel widening is a response to bank destabilization that results from either the removal of bank vegetation, an increase in sediment supply, or geotechnical failure following channel incision. For channel reaches that respond primarily through vertical channel movement, channel widening plays a more important role in high-energy environments than in low-energy environments (Simon 1992). In these systems, channel widening from bank failure contributes to energy dissipation by reducing hydraulic depths and stream power (Simon 1992). In channel reaches where lateral processes dominate channel response, channel widening takes place concurrently with channel braiding. Aggradation and braiding is driven by high bed-load supply (e.g., Smith and Smith 1984), variability of flow, bank instability, and a reduction in gradient (Knighton 1998). Channel widening may also occur in response to increases in the magnitude and frequency of peak flows associated with urbanization (e.g., Hammer 1972).

Narrowing
Like channel widening, channel narrowing occurs in a continuum of channel response and refers to a decrease in the top width of a stream through channel incision. Channel narrowing occurs as a stream recovers from a previous disturbance that initiates rapid aggradation (e.g., debris flow, alluvial fan formation, channel braiding) or from changes in boundary conditions (e.g., construction of a large dam, tectonic activity, climate change). Immediately following rapid aggradation, water flows across a wide, shallow channel and overtime will incise a narrower channel into the sediment deposits. Additionally, human constraints and maintenance activities (e.g., levees, riprap, dredging, log jam, and snag removal) can induce channel narrowing by physically disconnecting the channel from its floodplain. Channel narrowing also occurs following a change in base level elevation (e.g., from tectonics), which causes the channel to abandon its immediate floodplain. *Underfit channels* are streams that occupy former channel forms that were generated by a hydrologic regime with larger channel-forming flows (Dury 1976). Streams may become *underfit* following changes in the hydrologic regime that significantly reduce peak flows (e.g., from dams or climate change).

Vertical Movement

In a channel reach that is in equilibrium, the quantity of sediment entering the reach, I, will equal the quantity exported from the reach, E:

$$I - E = 0$$

Vertical change occurs when there is an imbalance in the sediment supply coming into and leaving a channel reach. A surplus in sediment supply occurs when I is greater than E and a deficit occurs when I is less than E. A surplus will lead to an increase in the channel bed elevation (aggradation) and a deficit will result in a decrease in the channel bed elevation (incision). Natural and artificial channel obstructions that impound flow, such as log jams and dams, have the most dramatic effect on vertical channel change within a channel reach. These structures trap sediment upstream, raise the streambed elevation, and create a sediment deficit downstream, thereby lowering channel bed elevation. Changes in transport capacity can also be as important as sediment supply in triggering vertical bed changes.

Incision

Channel incision occurs when the transport capacity greatly exceeds sediment supply (Bull 1979; Galay 1983) which occurs most commonly in disturbed systems, such as urbanized streams, leveed streams, or streams recovering from land use activities (e.g., gravel mining or forest management). Channel incision can also occur if in-stream roughness elements (e.g., snags, log jams), which provide energy dissipation and grade control, are removed. As an incising channel deepens, flow events of increasingly greater magnitudes are contained within the channel banks. This process can create positive feedback: erosional forces on the bed and toe of the banks are magnified during large events, causing greater incision. Channel incision can be followed by bank failure and channel widening if the banks of the incising channel reach a critical height and become prone to geotechnical failure (Darby and Simon 1999). If this occurs, the channel will eventually establish a new floodplain and form a quasi-equilibrium channel within the larger entrenched channel (Booth 1991; Bledsoe and Watson 2001).

Aggradation

Channel aggradation refers to the process of streambed and/or floodplain deposition, which causes a rise in elevation and a localized decrease in gradient. Aggradation is essentially the inverse of channel incision: sediment supply exceeds the transport capacity through the reach, which results in deposition. Aggradation occurs downstream of incising channels and upstream of areas that have experienced an increase in streambed elevation (e.g., base-level changes or an obstruction). Aggradation decreases the cross-sectional area of a channel and increases the frequency of overbank flooding. In unconfined reaches, log jams commonly raise channel bed elevations over 2 m (e.g., Abbe and Montgomery, in press), which can be above adjacent floodplains, and, in some instances, above fluvial terraces as well.

Appendix B: Channel Survey Field Sheets and Guidelines

Field studies are a necessary and significant component of delineating a CMZ, not only for the purpose of gathering empirical data, but especially when:

- historical data (aerial photographs, historical topographic maps, and historical surveys) is sparse in areal coverage and/or sporadic over time, with long gaps between survey dates;
- geomorphic changes in smaller channels are difficult to discern, or in larger channels the resolution of the data obscures channel forms and features; or
- in evolving and unstable systems, where channel movement is unsteady, non-uniform and complex, future channel movement cannot be extrapolated solely from historical data.

The content and organization of this section are adapted from Thorne (1998); field sheets for the channel survey are provided at the beginning of the section followed by guidelines for completing the field sheets. These sheets are provided here with the assumption that the analyst knows how to determine what data collection is necessary and thereby can adapt the field sheets accordingly in order to be able to use them to supplement historical studies and customize them to the geomorphic and management context of the study area. The analyst must have expertise in fluvial geomorphology in order to be able to correctly identify features in the field and interpret geomorphic processes acting on the channel. In short, elements of the field sheets are subjective, which means academic and professional experience in fluvial geomorphology is essential in order for the analyst to make proper use of them.

Field Equipment

For measuring distances and channel dimensions:

- Rangefinder, or
- Hip chain string pedometer, or
- Measuring tape with survey pins and flagging tape
- Optional level and rod

For surveying cross-sections and channel profiles:

- Leveling instrument (hand level, optical autolevel, or laser level); theodolite or total station and tripod
- Rod or survey staff
- Clinometer
- Compass
- GPS

For measuring flow measurements (as necessary):

- Flow meter
- Depth meter or rod

For photographically documenting the study area:

- 35 mm or digital camera
- GPS

For mapping and referencing the study area:
- Recent orthophoto rectified aerial photographs with scale (laminated)
- Mylar sheets overlain on aerial photographs (for mapping channel system)
- Water resistant field book and pen ("Rite in the Rain" books and pens)
- Topographic maps
- Geologic map
- Local plant identification sheets
- Metric ruler (pebble counts and map measurements)
- GPS

B.1 Field Sheets

CHANNEL SURVEY RECORD SHEET

Developed by Colin R. Thorne
Adapted by Cygnia F. Rapp and Timothy B. Abbe

SECTION 1 - SCOPE AND PURPOSE

Brief Problem Statement:

Purpose of Stream Reconnaissance:

Logistics of Reconnaissance Trip:

RIVER LOCATION DATE

PROJECT STUDY REACH From To

SHEET COMPLETED BY

RIVER STAGE TIME: START TIME: FINISH

General Notes and Comments on Reconnaissance Trip:

SECTION 2 - REGION AND VALLEY DESCRIPTION

PART 1: CHANNEL VALLEY SIDES

Location of River	**Height**	**Side Slope Angle**	**Valley Side Failures**	***Interpretative Observations*** ***Material Type***	***Severity of Problems***
In Valley ☐	<5 m ☐	< 5 degrees ☐	None ☐	*Bedrock* ☐	*Insignificant* ☐
On Alluvial Fan ☐	5-10 m ☐	5-10 degrees ☐	Occasional ☐	*Soils* ☐	*Moderate* ☐
On Alluvial Plain ☐	10-30 m ☐	10-20 degrees ☐	Frequent ☐	*Loose debris* ☐	*Severe* ☐
In a Delta ☐	30-60 m ☐	20-50 degrees ☐	**Failure Locations**		*Catastrophic* ☐
In Old Lake Bed ☐	60-100 m ☐	>50 degrees ☐	None ☐		
	>100 m ☐		Away from river ☐		
			Along river (Undercut) ☐		

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

PART 2: CHANNEL TERRACE SIDES

Terrace Topography	**Terrace Height**	**Side Slope Angle**	**Terrace Side Failures**	***Interpretative Observations*** ***Material Type***	***Severity of Problems***
None ☐	< 5 m ☐	< 5 degrees ☐	None ☐	*Bedrock* ☐	*Insignificant* ☐
Indefinate ☐	5-10 m ☐	5-10 degrees ☐	Occasional ☐	*Soils* ☐	*Moderate* ☐
Fragmentary ☐	10-30 m ☐	10-20 degrees ☐	Frequent ☐	*Loose debris* ☐	*Severe* ☐
Continuous ☐	30-60 m ☐	20-50 degrees ☐			*Catastrophic* ☐
	60-100 m ☐	>50 degrees ☐	**Failure Locations**		
Number of Terraces ___	>100 m ☐		None ☐		
			Away from river ☐		
			Along river (Undercut) ☐		

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

PART 3: FLOOD PLAIN (VALLEY FLOOR)

Valley Floor Width	**Surface Geology (Relative %)**	**Land Use (Relative %)**	**Vegetation (Relative %)**	**Riparian Buffer Length**
None ☐	Bedrock ☐	Undisturbed ☐	None ☐	None ☐
<2 River width ☐	Glacial moraine ☐	Managed forest ☐	Grass/pasture ☐	Fragmentary ☐
2-4 River widths ☐	Glacial outwash ☐	Agriculture ☐	Orchards ☐	Continuous ☐
4-10 River widths ☐	Fluvial: alluvium ☐	Urban ☐	Arable crops ☐	**Riparian Buffer Width**
>10 River widths ☐	Fluvial: wetlands ☐	Suburban ☐	Shrubs ☐	None ☐
	Lake deposits ☐	Industrial ☐	Deciduous forest ☐	<1 River width ☐
Flow Resistance*	Wind blown (Loess) ☐	= 100%	Coniferous forest ☐	1-5 River widths ☐
Left Overbank Manning n value ___	= 100%		Mixed forest ☐	>5 River widths ☐
Right Overbank Manning n value ___	(*note: n value for channel is recorded in Part 6)		= 100%	

Notes and Comments:

PART 4: VERTICAL RELATION OF CHANNEL TO VALLEY

Trash and Silt Lines	Overbank Deposits	Levees	Levee Data	*Interpretative Observations*
Absent	None	None	Height (m)	***Present Status***
Present	Silt	Natural	Side slope (o)	*Adjusted*
Height above floodplain (m) ___	Fine sand	Constructed		*Incised*
	Medium sand	**Levee Description**	**Levee Condition**	*Aggraded*
	Coarse sand	None	None	***Anticipated Instability***
Log Jams	Gravel	Fragmentary	Intact	*Stable*
Log steps	Boulders	Continuous	Local failures	*Degrading*
Valley jams	Woody debris	Left bank	Frequent failures	*Aggrading*
	Trash	Right bank		
	Thickness (m) ___	Both banks		

Problem Severity: *Insignificant*, *Moderate*, *Severe*

Problem Extent: *None*, *Local*, *Reach-scale*, *System-wide*, *Regional*

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

PART 5: LATERAL RELATION OF CHANNEL TO VALLEY

Planform	Planform Data	Lateral Activity	Floodplain Features	*Interpretative Observations*
Straight	*Max/Min:*	None	None	***Present Status***
Meandering	Bend radius ___	Meander progression	Secondary channels	*Adjusted*
Braided	Meander belt width ___	Increasing amplitude	Scroll bars	*Over wide*
Anastomosed	Wavelength ___	Irregular erosion	Oxbow lakes	*Too narrow*
Delta		Avulsion	Irregular terrain	***Anticipated Instability***
Alluvial Fan	*Reach Average:*	Channel widening	Splay deposits	*Stable*
	Meander sinuosity ___	Channel narrowing	Uniform forest age	*Widening*
Log Jams		**Location in Valley**	Mixed forest age	*Narrowing*
Flow deflection jams		Left	Old forest patches	
Bench jams		Middle		
Bar apex jams		Right		
Meander jams				

Problem Severity: *Insignificant*, *Moderate*, *Severes*

Problem Extent: *None*, *Local*, *Reach-scale*, *System-wide*, *Regional*

Level of Confidence in percent (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

SECTION 3 - CHANNEL DESCRIPTION

PART 6: CHANNEL DESCRIPTION

		Bed Control Types	**Bed Control Frequency**	**Width Control Types**	**Width Control Freq.**
Dimensions	**Flow Type**	None ☐	None ☐	None ☐	None ☐
Av. top bank width (m) ___	None ☐	Bedrock ☐	Occasional ☐	Bedrock ☐	Occasional ☐
Av. channel depth (m) ___	Uniform/tranquil ☐	Boulders ☐	Frequent ☐	Revetments/riprap ☐	Frequent ☐
Av. water width (m) ___	Uniform/rapid ☐	Cohesive materials ☐	Confined ☐	Bridge abutments ☐	Confined ☐
Av. water depth (m) ___	Pool + riffle ☐	Man-made structures ☐	Number of controls ___	Levees or groynes ☐	No. of controls ___
Reach slope ___	Steep + tumbling ☐	Woody debris ☐		Cohesive materials ☐	
Mean velocity (m/s) ___	Steep + step-pool ☐			Woody debris ☐	
Manning's n value ___	(Note: Flow type on day of observation)				

Notes and Comments:

PART 7: BED SEDIMENT DESCRIPTION

Bed Material	**Bed Armor**	**Surface Size Data**	**Bed Forms (Sand)**	**Bar Types**	**Bar Surface data**
Clay ☐	None ☐	D50 (mm) ___	Flat bed (None) ☐	None ☐	D50 (mm) ___
Silt ☐	Static-armor ☐	D84 (mm) ___	Ripples ☐	Pools + riffles ☐	D84 (mm) ___
Sand ☐	Mobile-armor ☐	D16 (mm) ___	Dunes ☐	Point bars ☐	D16 (mm) ___
Sand + gravel ☐			Bed form height (m) ___	Mid-channel bars ☐	
Gravel + cobbles ☐	**Sediment Depth**	**Substrate Size Data**	**Bars**		**Bar Substrate data**
Cobbles + boulders ☐	Depth of loose	D50 (mm) ___	None ☐		D50 (mm) ___
Boulders + bedrock ☐	Sediment (cm) ___	D84 (mm) ___	Occasional ☐		D84 (mm) ___
Bedrock ☐		D16 (mm) ___	Frequent ☐		D16 (mm) ___

Notes and Comments:

Channel Sketch Map

Map Symbols

Study reach limits	u/s limit d/s limit	North point	N	Cut bank		Photo point	P1
Cross-section	A—A′	Flow direction		Exposed island/bar		Sediment sampling point	S2
Bank profile	B3	Impinging flow		Structure		Significant vegetation	
Log jam		Snag					

Representative Cross-Section

SECTION 4 - LEFT BANK SURVEY

PART 8: LEFT BANK CHARACTERISTICS

Type
- Noncohesive ☐
- Cohesive ☐
- Uniform ☐
- Layered ☐
- Number of layers ___

Protection Status
- Unprotected ☐
- Hard points ☐
- Toe protection ☐
- Revetments/riprap ☐
- Levees ☐

Bank Materials

Material	*1*	*2*	*3*	*4*
Silt/clay				
Sand/silt/clay				
Sand/silt				
Sand				
Sand/gravel				
Gravel				
Gravel/cobbles				
Cobbles				
Cobbles/boulders				
Boulders/bedrock				

Layer Thickness
- Material 1 (m) ___
- Material 2 (m) ___
- Material 3 (m) ___
- Material 4 (m) ___

Bank Profile Shape
(see **Figures B-6**) ______

Ave. Bank Height
Average height (m) ___

Ave. Bank Slope
Angle (degrees) ___

Tension Cracks
- None ☐
- Occasional ☐
- Frequent ☐

Crack Depth
Proportion of bank height ___

Notes and Comments:

PART 9: LEFT BANK-FACE VEGETATION

Vegetation
- None/fallow ☐
- Artificially cleared ☐
- Grass ☐
- Reeds and sedges ☐
- Shrubs ☐
- Saplings ☐
- Trees ☐

Orientation
Angle of leaning (o)

Tree Types
- None ☐
- Deciduous ☐
- Coniferous ☐
- Mixed ☐

Tree species
(if known)
______
______
______

Density + Spacing
- None ☐
- Sparse/clumps ☐
- Dense/clumps ☐
- Sparse/continuous ☐
- Dense/continuous ☐

Roots
- Normal ☐
- Exposed ☐
- Adventitious ☐

Location
- Whole bank ☐
- Upper bank ☐
- Mid-bank ☐
- Lower bank ☐

Diversity
- Mono-stand ☐
- Mixed stand ☐
- Climax-vegetation ☐

Health
- Healthy ☐
- Fair ☐
- Poor ☐
- Dead ☐

Age
- Immature ☐
- Mature ☐
- Old ☐
- Age in years

Height
- Short ☐
- Medium ☐
- Tall ☐
- Height (m) ___

Lateral Extent
- Wide belt ☐
- Narrow belt ☐
- Single row ☐

Notes and Comments:

Bank Profile Sketches

Profile Symbols

Bank Top Edge	Failed debris	Engineered Structure
Bank Toe	Attached bar	Significant vegetation
Water's Edge	Undercutting	Vegetation Limit

PART 10: LEFT BANK EROSION AND SHORELINE ACCRETION

Erosion Location	**Present Status**	**Rate of Retreat**
Outside meander ☐	Intact ☐	m/yr (if applicable
Inside meander ☐	Eroding:dormant ☐	and known) ___
Opposite a bar ☐	Eroding:active ☐	
Behind a bar ☐	Advancing:dormant ☐	**Rate of Advance**
Opposite a structure ☐	Advancing:active ☐	m/yr (if applicable
Adjacent to structure ☐		and known) ___
Dstream of structure ☐		
Ustream of structure ☐		
Other (write in) ☐		

Interpretative Observations

Extent of Erosion	***Severity of Erosion***	***Processes***
None ☐	*Insignificant* ☐	*Parallel flow* ☐
Local ☐	*Moderate* ☐	*Impinging flow* ☐
Reach-scale ☐	*Severe* ☐	*Other (write in)* ☐
System-wide ☐	*Catastrophic* ☐	☐

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

PART 11: LEFT BANK GEOTECHNICAL FAILURES

Failure Location		**Present Status**		**Failure Scars + Blocks**		***Instability—Severity***		***Instability—Extent***	
Outside meander	☐	Stable	☐	None	☐	*Insignificant*	☐	*None*	☐
Inside meander	☐	Unreliable	☐	Old	☐	*Moderate*	☐	*Local*	☐
Opposite a bar	☐	Unstable:dormant	☐	Recent	☐	*Severe*	☐	*Reach-scale*	☐
Behind a bar	☐	Unstable:active	☐	Fresh	☐	*Catastrophic*	☐	*System-wide*	☐
Opposite a structure	☐								
Adjacent to structure	☐								
Dstream of structure	☐								
Ustream of structure	☐								
Other (write in)	☐								

Interpretative Observations

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

SECTION 5 - RIGHT BANK SURVEY

PART 12: RIGHT BANK CHARACTERISTICS

Type
- Noncohesive ☐
- Cohesive ☐
- Uniform ☐
- Layered ☐
- Number of layers ___

Protection Status
- Unprotected ☐
- Hard points ☐
- Toe protection ☐
- Revetments ☐
- Levee ☐

Bank Materials

Material	*1*	*2*	*3*	*4*
Silt/clay				
Sand/silt/clay				
Sand/silt				
Sand				
Sand/gravel				
Gravel				
Gravel/cobbles				
Cobbles				
Cobbles/boulders				
Boulders/bedrock				

Layer Thickness
- Material 1 (m) ___
- Material 2 (m) ___
- Material 3 (m) ___
- Material 4 (m) ___

Bank Profile Shape
(see **Figure B-6**) ______

Ave. Bank Height
Average height (m) ___

Ave. Bank Slope
Angle (degrees) ___

Tension Cracks
- None ☐
- Occasional ☐
- Frequent ☐

Crack Depth
Proportion of bank height ___

Notes and Comments:

PART 13: RIGHT BANK-FACE VEGETATION

Vegetation
- None/fallow ☐
- Artificially cleared ☐
- Grass ☐
- Reeds and sedges ☐
- Shrubs ☐
- Saplings ☐
- Trees ☐

Orientation
Angle of leaning (o)

Tree Types
- None ☐
- Deciduous ☐
- Coniferous ☐
- Mixed ☐

Tree species
(if known)
______
______
______

Density + Spacing
- None ☐
- Sparse/clumps ☐
- Dense/clumps ☐
- Sparse/continuous ☐
- Dense/continuous ☐

Roots
- Normal ☐
- Exposed ☐
- Adventitious ☐

Location
- Whole bank ☐
- Upper bank ☐
- Mid-bank ☐
- Lower bank ☐

Diversity
- Mono-stand ☐
- Mixed stand ☐
- Climax-vegetation ☐

Health
- Healthy ☐
- Fair ☐
- Poor ☐
- Dead ☐

Age
- Immature ☐
- Mature ☐
- Old ☐
- Age in years

Height
- Short ☐
- Medium ☐
- Tall ☐
- Height (m) ___

Lateral Extent
- Wide belt ☐
- Narrow belt ☐
- Single row ☐

Notes and Comments:

Bank Profile Sketches

Profile Symbols

Bank Top Edge	Failed debris	Engineered Structure
Bank Toe	Attached bar	Significant vegetation
Water's Edge	Undercutting	Vegetation Limit

PART 14: RIGHT BANK EROSION AND SHORELINE ACCRETION

Erosion Location	Present Status	Rate of Retreat
Outside meander ☐	Intact ☐	m/yr (if applicable and known) ___
Inside meander ☐	Eroding:dormant ☐	
Opposite a bar ☐	Eroding:active ☐	
Behind a bar ☐	Advancing:dormant ☐	**Rate of Advance**
Opposite a structure ☐	Advancing:active ☐	m/yr (if applicable and known) ___
Adjacent to structure ☐		
Dstream of structure ☐		
Ustream of structure ☐		
Other (write in) ☐		

Interpretative Observations

Extent of Erosion	*Severity of Erosion*	*Processes*
None ☐	*Insignificant* ☐	*Parallel flow* ☐
Local ☐	*Moderate* ☐	*Impinging flow* ☐
Reach-scale ☐	*Severe* ☐	*Other (write in)* ☐
System-wide ☐	*Catastrophic* ☐	☐

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

PART 15: RIGHT BANK GEOTECHNICAL FAILURES

Failure Location		**Present Status**		**Failure Scars + Blocks**		***Instability—Severity***		***Instability—Extent***	
Outside meander	☐	Stable	☐	None	☐	*Insignificant*	☐	*None*	☐
Inside meander	☐	Unreliable	☐	Old	☐	*Moderate*	☐	*Local*	☐
Opposite a bar	☐	Unstable:dormant	☐	Recent	☐	*Severe*	☐	*Reach-scale*	☐
Behind a bar	☐	Unstable:active	☐	Fresh	☐	*Catastrophic*	☐	*System-wide*	☐
Opposite a structure	☐								
Adjacent to structure	☐								
Dstream of structure	☐								
Ustream of structure	☐								
Other (write in)	☐								

Interpretative Observations

Level of Confidence in answers (Circle one)

0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:

B.2 Guidelines for Completing Field Sheets

The field sheets are separated into five major sections. Each section is divided into parts that deal with different elements of the section. Space is provided at the end of each part for notes and comments. The sheets have been designed to assist the analyst in providing a comprehensive data collection record of the form, features, and processes of a stream channel and its surroundings. They are applicable to a wide range of types and sizes of rivers in diverse settings. In the instances where the analyst has very little background data, these field sheets provide a comprehensive approach for the analyst to evaluate channel processes on a reconnaissance level; however, at this point in the CMZ study, the analyst should have, at the minimum, divided the study area into channel reaches according to their erosional characteristics, channel pattern, confinement, and sedimentology (refer to **Section 3** of the main document).

If the study area has multiple sets of reach types, then the field team will need to survey a minimum of one reach from each reach type. Although survey results from one reach type could be used to extrapolate channel behavior in other reaches with relatively homogenous characteristics, questions from aerial photo studies may necessitate the analyst to walk or float substantial lengths of stream, floodplain, and secondary channels to verify or update photo interpretations.

B.2.1 Section 1 – Scope and Purpose

This field sheet is used by the analyst to create an overview of the basic questions and objectives that should be defined prior to beginning the field work. It is also for the analyst to record the logistical information on when and by whom the fieldwork was performed and provides space for notes on the geographic limits of the study area. At this stage in the CMZ study, the analyst should have identified erosional and depositional features from aerial photos and decided what field measurements are needed (and possible) from preliminary site visits.

B.2.2 Section 2 – Region and Valley Description

These field sheets are used by the analyst to document the valley-wide perspective that will aid in interpretation of channel dynamics, and to describe the valley and floodplain that surrounds the stream channel. They also allow the analyst to document the geomorphic relationship between the channel and its valley and terrace walls.

Part 1: Channel Valley Sides

This part has seven topics that the analyst can use to define the form, scale, geometry, stability, and mode of failure (if any) of the valley side slopes, and the severity of any sediment-related problems.

Location of River: mark whether the river is in a valley or is located in some other physiographic setting such as on an alluvial fan, plain, delta, or lake bed. If there are no valley sides, the analyst will not complete the remainder of this section.

Height** and **Side Slope Angle: record the scale and geometry of the valley sides. (The higher and/or steeper the valley sides, the greater their potential to drive large-scale channel instability through the input of debris or sediment into the fluvial system.)

Valley Side Failures: record whether the side slopes are stable or are prone to either occasional or frequent mass wasting. (Valley wall failures indicate large-scale, lateral geomorphic activity and, possibly sustained valley widening. Such activity is clear evidence of contemporary erosion of the landscape.)

***Failure Locations**:* indicate whether failures are adjacent (coupled) to or apart (uncoupled) from the fluvial system. (This determines the relationship between the river and any failures—e.g., failures occurring away from the river are not a direct result of river erosion—and indicates how debris or sediment derived from valley side failures is delivered to the river.)

Interpretive Observations: these two topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Material Type: record whether the composition of the valley side materials is bedrock, soil, or unconsolidated debris. Debris in this context is a surficial collection of broken rock usually referred to as *talus*.

Severity of Problems: indicate the level of impact of valley side failures on the valley environment. (Unstable valley sides can cause severe sedimentation locally and farther downstream in the process of supplying large volumes of both coarse sediment and wash load to the fluvial system.)

Part 2: Channel Terrace Sides

This part has seven topics that the analyst can use to define the form, scale, geometry, stability and mode of failure (if any) of the terrace side slopes, and the severity of any sediment-related problems.

***Terrace Topography*:** If there are no terrace sides, the analyst will mark "None" and will not complete the remainder of this section.

***Number of Terraces*:** record how many terrace elevations are identifiable.

***Height** and **Side Slope Angle**:* define the scale and geometry of the terrace sides. (The higher and/or steeper the terrace sides, the greater their potential to drive large-scale channel instability by supplying debris or sediment into the fluvial system.)

Terrace Side Failures: record whether the side slopes are stable, or prone to either occasional or frequent failures. (Terrace wall failures indicate large-scale, lateral geomorphic activity and, possibly sustained valley widening. Such activity is clear evidence of significant, contemporary erosion of the landscape.)

Failure Locations: indicate whether failures are adjacent (coupled) to or apart (uncoupled) from the fluvial system. (This determines the relationship between the river and any failures—e.g., failures occurring away from the river are not a direct result of river erosion—and indicates how debris or sediment derived from terrace side failures is delivered to the river.)

Interpretive Observations: these two topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Material Type: record whether the composition of the terrace side materials is bedrock, soil, or unconsolidated debris. Debris in this context is a surficial collection of broken rock usually referred to as talus.

Severity of Problems: indicate the level of impact of terrace side failures on the valley environment. (Unstable terrace faces can cause severe sedimentation locally and farther downstream in the process of supplying large volumes of coarse sediment and wash load to the fluvial system.)

Part 3: Floodplain (Valley Floor)

This part has seven topics that the analyst can use to characterize the size, geology, landuse, and vegetation of the low-lying area around the river channel, extending to the valley and/or terrace sides.

Valley Floor Width: note the relative confinement of the channel and its floodplain. (Rivers with narrow floodplains are closely coupled with runoff and erosion processes operating on the valley and terrace sides and susceptible to destabilization by valley and terrace side slope failures.)

Flow Resistance: record the Manning's "n" coefficient for the left and right overbank areas. ("n" values are used for modeling water and sediment movement during overbank flow events.)

Surface Geology: record the origin of the surficial materials that comprise the floodplain or valley floor. (Erosion resistance is directly related to surficial geology which strongly affects the susceptibility of the area to channel migration, avulsion, and impacts to downstream sediment transport.)

Land Use: record the type of human activity (if any) taking place on the floodplain or valley floor. (Generally, channels in rural areas are less affected by revetments and flood control structures compared to those in urban or industrially developed floodplains.)

Vegetation: record the vegetation assemblage. (Vegetation plays several important roles in floodplain hydrology, bank protection, overbank hydraulics, and sediment dynamics. It is useful to know the vegetation assemblage on the floodplain for gaging its influence on present hydrologic, hydraulic and sediment processes, and to assess potential bank instability induced by changes in vegetation.)

Riparian Buffer Length and Riparian Buffer Width: note the presence and the extent of any treed, vegetative corridor along the course of a river.

Part 4: Vertical Relation of Channel to Valley

This part has ten topics that the analyst can use to establish how the channel interacts vertically with its valley bottom, to record landforms and processes, and to indicate the presence or absence of vertical instability.

Trash and Silt Lines: mark whether there is evidence of trash and silt lines or not and (if present) their height above the floodplain. (Keep in mind the elevation of flood debris and trash lines mark the minimum water surface elevation of the corresponding flood, given these materials are deposited on the receding limb of the hydrograph.)

Overbank Deposits: note the general thickness and caliber of any material that may have been deposited onto the valley floor by overbank flow. (Vertical accretion of the floodplain during floods is normal in a dynamically stable system, but especially heavy overbank deposition may indicate accelerated floodplain sedimentation that may be associated with aggradation and valley filling.)

Log Jams: record the presence of log steps and valley jams. (These two jam types [Figure B-1] are primarily applicable to grade control and vertical bed aggradation [Abbe 2000; Abbe et al. 2003] and initiate channel bed aggradation and force morphologies typical of response reaches by reducing channel gradient and redistributing energy loss through the reach. Log steps, also termed step jams or multi-log weirs, form when a tree bole spans the channel with each end locked in place along the channel margins by rock boulders, woody debris, or sediments. Valley jams are large, complex grade control structures found in channels with gradients ranging from 2% to over 20%.)

1. Log Step

2. Valley Jam

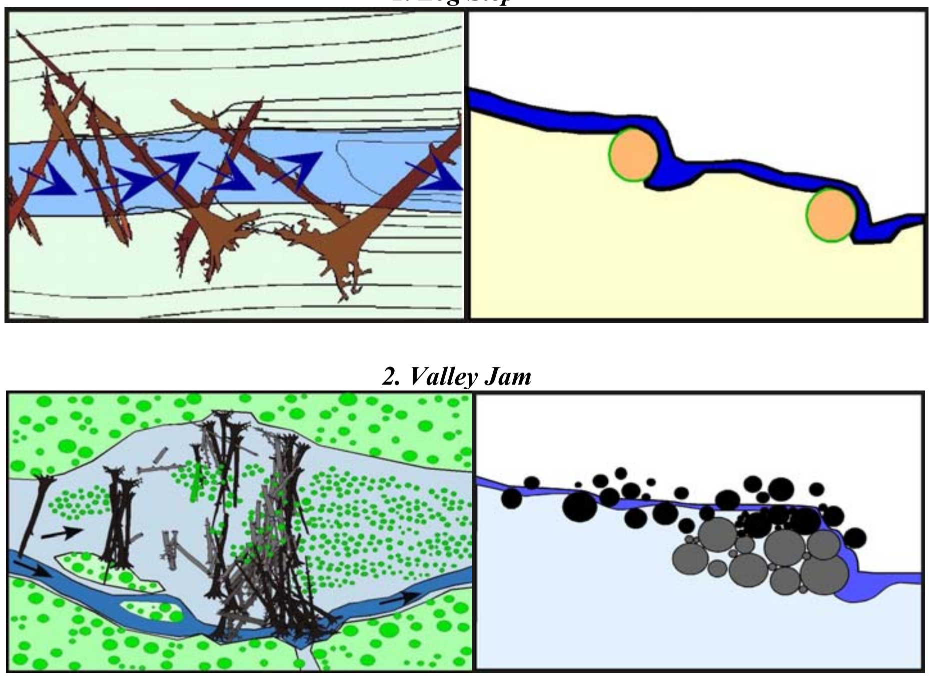

Figure B-1. Planforms and cross-sections of log jams that primarily act as grade control (adapted from Abbe et al. 2003).

***Levees and Levee Description*: **if levees are present, record whether they are natural or man-made and mark whether they are fragmented or not and the banks they are on. (Natural levees are produced by overbank sedimentation during flood flows because the greatest amount of sediment is deposited close to the river; prominent natural levees indicate a river with a heavy sediment load and frequent overbank flooding and are clear evidence of active floodplain sedimentation. Man-made levees are constructed to contain flood flows and protect the area behind them from inundation; they may be set back some distance behind the bank top and their presence indicates that in the past the river has generated overbank flow in this area.)

Levee Data and Levee Condition: record the height, side slope angle, and stability of any levees present.

Interpretive Observations*:* these four topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Present Status: define whether the channel in the study reach is presently adjusted to the valley floor elevation (graded), or whether it is incised or aggraded. (Incised rivers rarely flood because of undercutting and mass failure of the channel banks by flows concentrated within the channel. Aggraded rivers often flood, thereby depositing sediment on their floodplains and building natural levees; they have high width-to-depth ratios, numerous bars and islands, a poorly defined thalweg, and widen through erosion of bank material.)

Anticipated Instability: define whether vertical instability in the system is ongoing (degrading or aggrading) or has discontinued (is stable). (Although the present status of the channel is important, the analyst must make predictions of future channel movement by considering upstream and downstream activities and consulting historical studies.)

Problem Severity: define the level of severity of any contemporary vertical instability. (Not every symptom of vertical adjustment in the fluvial system causes serious problems; this topic puts any sediment impacts associated with aggradation or degradation into a management perspective.)

Problem Extent: define the scale of vertical instability in the river. (This is usually an important step for identifying the underlying cause of channel instability: if a problem is widespread throughout the fluvial system, then a local, structural solution may be ineffective; for success, it is usually necessary to match the scale of the solution to the scale of the problem.)

Part 5: Lateral Relation of Channel to Valley

This part has nine topics that the analyst can use to establish how the channel interacts laterally with the valley bottom, and to record those fluvial landforms that indicate lateral instability and/or channel migration. (Indicators of lateral activity include channel planform geometry, type of planform evolution, and topographic features on the floodplain surface.)

Planform: describe the geometry of the channel as viewed from above, using the generally accepted classification of rivers (see **Appendix A**) as being straight, meandering, braided, or anastomosing. (In reality there is a continuum of river patterns, with every channel displaying some elements of all four patterns.)

Planform Data: record the characteristic dimensions of any meanders (**Figure B-2**). (Radius of curvature measures the tightness of the bend in terms of the radius of a circle approximately following the channel centerline. Meander belt width is the historical width of the strip of floodplain previously occupied by the channel as bends migrate laterally and downstream. Wavelength is twice the long-valley distance between meander inflection points, which essentially includes two meanders. Meander sinuosity is the channel length divided by the straight line valley length.)

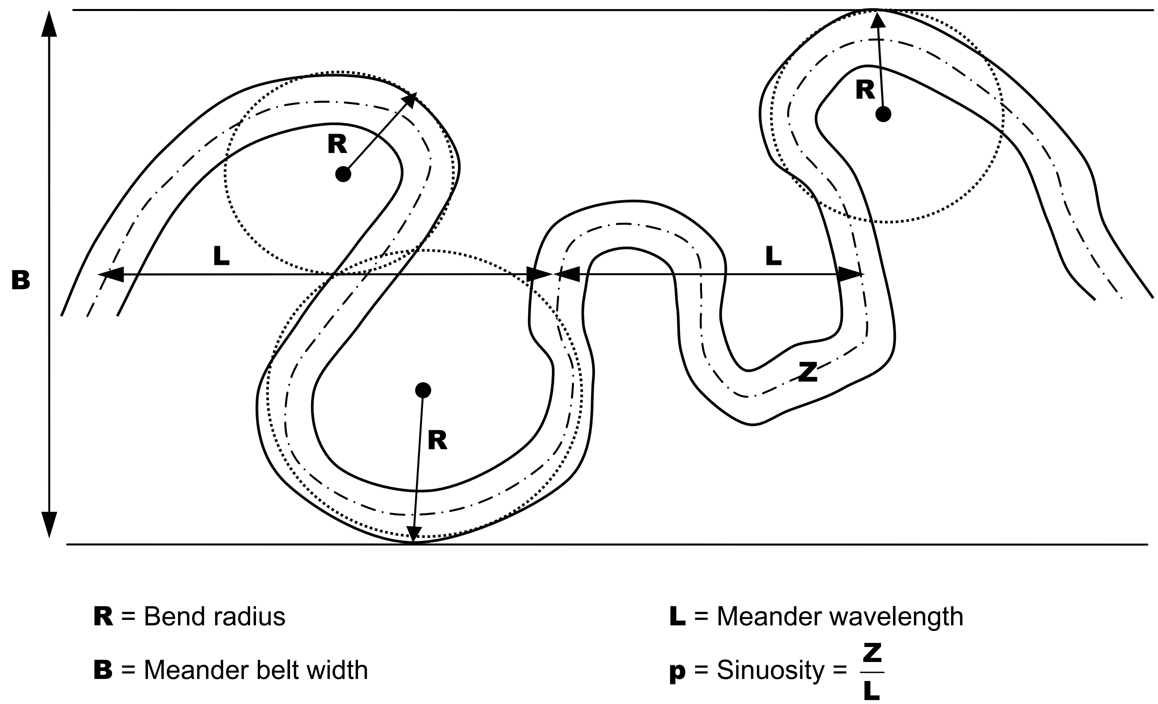

Figure B-2. Definition of meander planform parameters.

Log Jams: record the presence of flow deflection jams, bench jams, bar apex jams, and meander jams that manipulate flow, and thereby provide bank protection, accelerate bank erosion, and/or initiate avulsion. (These four types [**Figure B-3**] are primarily applicable to flow manipulation [Abbe 2000; Abbe et al. 2003]. Flow deflection jams are found in relatively large channels with moderate gradients. These structures form initially when large trees [key members] fall into the river and deflect flow; with time these structures become integrated into a new river bank and are classified as bank protection or revetment types structures, as opposed to flow diversion structures. Bench jams are typically found in small, steep channels—slopes greater than 2%—where large logs become wedged into the margins of a channel and create local revetments that protect floodplain deposits and vegetation; where these structures occur, wood forms the stream bank and prevents erosion of alluvium stored behind them. Bar apex jams, a principal mechanism in the formation of anastomosing channel systems in the Pacific Northwest, resemble an upstream pointing arrowhead and typically occur at the upstream end of mid-channel bars and forested islands; found in large channels with low to moderate gradients, they are bi-directional flow diversion structures that create forest refugia in channel migration zones and are responsible for much of the channel complexity and pool formation in these systems. Meander jams occur in large alluvial rivers along the outer margins of meander bends; although many of these jams are accumulations of unstable debris that were deposited in shallow portions of the channel, some are stable structures that, unlike flow deflection jams, are composed of transported debris; meander jams, a principal cause of channel avulsions in Pacific Northwest rivers [Abbe et al. 2003], establish local—sub-reach scale—hard points within alluvial valleys, which limit channel migration and influence meander curvature.)

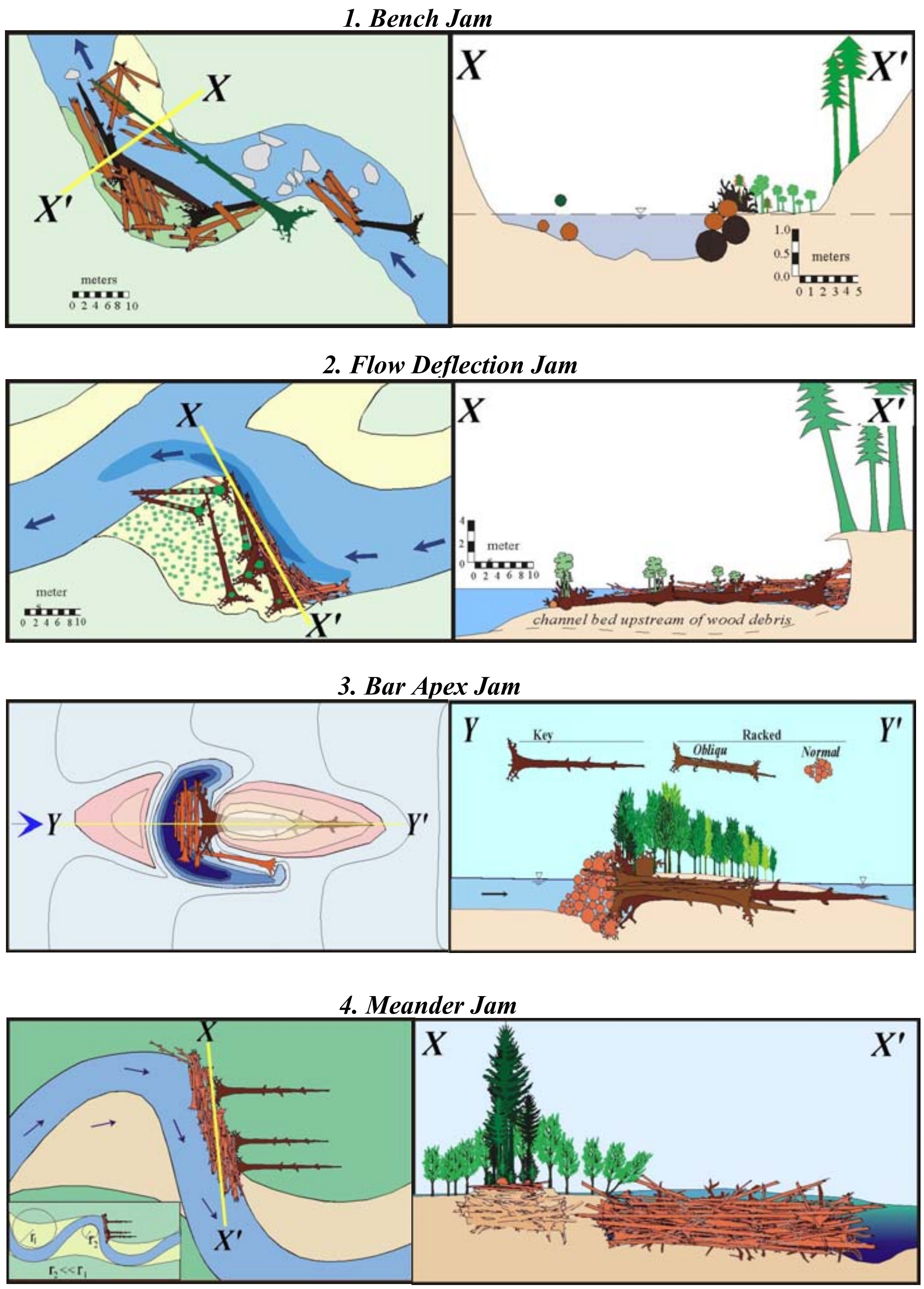

Figure B-3. Planforms and cross-sections of log jams that primarily manipulate flow (adapted from Abbe et al. 2003).

Lateral Activity: record the type of channel planform evolution (**Figure B-4**) that is currently taking place. (Meander progression—down valley movement of meander bends—occurs when bank erosion in meander bends is concentrated at the outer bank between the bend apex and the downstream crossing. Increasing amplitude occurs when the meander grows laterally. Irregular erosion occurs where variability in the erosion resistance of the banks disrupts the regular pattern of lateral activity. Avulsion occurs with the rapid abandonment of the river's present course in favor of a new one. Channel widening occurs when channel banks expand in response to geotechnical failure of the banks or from rapid aggradation that has led to a decrease in flow capacity. Channel narrowing occurs with a decrease in the top width of a stream via channel incision or from an increase in bank resistance from vegetation.

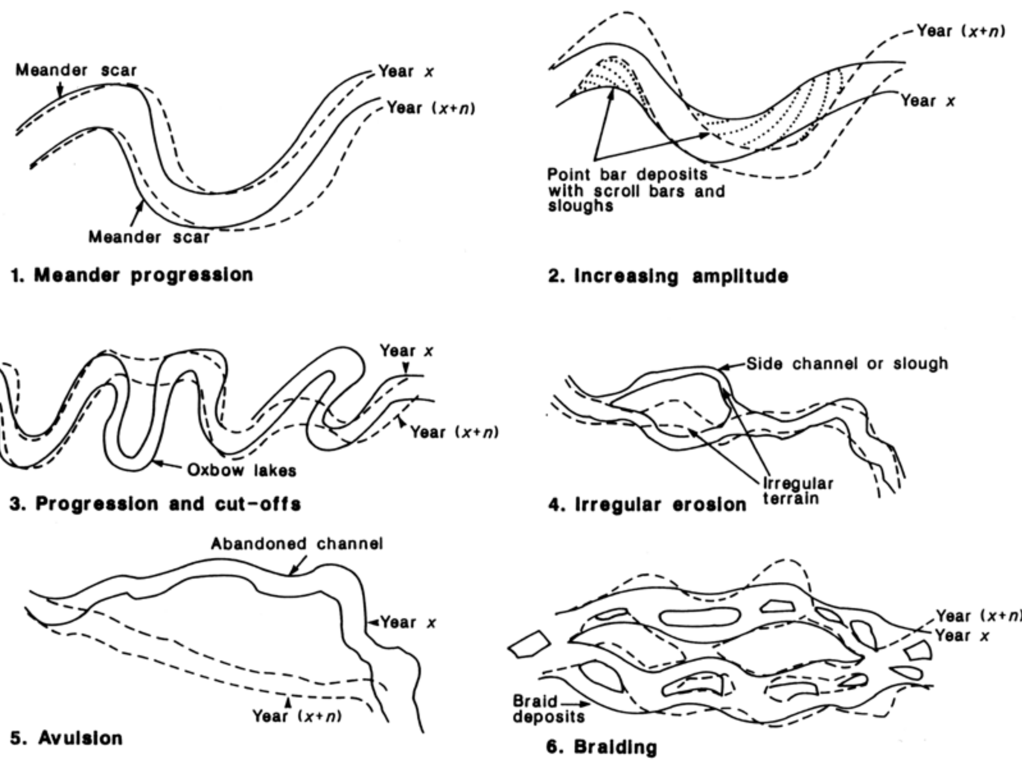

Figure B-4. Types of lateral activity and typical associated floodplain features (Thorne 1998).

Location in Valley: from the downstream direction, determine whether the channel is located to the right, left, or in the middle of the valley.

Floodplain Features: record any such features that are present. (Floodplain features vary with different types of lateral activity [**Figure B-4**]. Secondary channels represent the most likely pathways for future channel occupation; they include vegetated and unvegetated channels that convey water during flood events, as well as relic and abandoned channel features that once carried the main active channel but now convey water during periods of high flow. Scroll bars—low, curved ridges in the floodplain—are produced by point bar migration on the advancing, convex bank during meander growth and are found inside and roughly parallel to meander loops. Oxbow lakes are crescent-shaped water bodies that were once part of a meander bend, but have been abandoned due to a neck cut-off. Splay deposits–compressive forces along the channel bank—cause a lateral extension onto the floodplain, such as on the outside of a meander bend, and occur at weak points along the channel bank that are less resistant to erosion; they also occur as a precursor to avulsion. Uniform forest age denotes trees in a stand that are of similar species and age, while mixed forest age denotes trees in a stand that have a complex assemblage of species and ages. Old forest patch denotes mature conifers in a stand, or "island," within a younger stand of deciduous trees, which usually indicates that a buried log jam has survived channel erosion due to its revetment properties: buried log jams allow for old growth timber to persist within the active channel because of their stability.)

Interpretive Observations: these four topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Present Status: define whether or not the channel width is adjusted to the present flow, sediment, and woody debris regime. (Adjusted channels have stable widths over time, although they may still be laterally active. Over-wide channels are broad and shallow with shifting bars, and have stable banks with accumulated sediment shelves at the toes of both banks, which present a composite, two-stage channel in cross-section. Narrow—under-wide—rivers have low width-to-depth ratios, active erosion of both banks, little sediment stored at either bank toe, and somewhat trapezoidal cross-sections.)

Anticipated Instability: define whether lateral instability in the system is ongoing (widening: net bank erosion through retreat of one or both banks, or narrowing: net bank accretion through advance of one or both banks) or has discontinued (is stable). (Although the present status of the channel is important, the analyst must make predictions of future channel behavior by interpreting the current trend of channel change and extrapolating these trends through time.)

Problem Severity: define the level of severity of any lateral instability. (Not every symptom of lateral adjustment in the fluvial system causes serious problems; this topic places any sediment impacts associated with lateral instability and/or channel migration into a management perspective.)

Problem Extent: define the scale of lateral instability in the river; this is usually an essential step towards identification of the underlying cause of an instability problem.

B.2.3 Section 3 – Channel Description

This section focuses on the channel itself and is divided into two parts: channel description and bed sediment description; it enables the analyst to establish a clear picture of the dimensions, flow type, geologic or man-made controls on vertical and lateral activity, the composition of bed sediments, and the presence of sedimentary features. The geomorphic processes operating on the channel bed and banks are linked to each other, and should therefore be considered together. The dynamics between the channel bed and banks are relevant for channel classification and provide important clues regarding the cause, severity, and extent of any underlying channel instability. They also help indicate the sensitivity of the channel to destabilization through engineering or management activities. It is essential to establish these geomorphic characteristics so the channel can be analyzed and classified correctly. These qualitative and semi-quantitative observations are useful for interpreting the numerical information in cross-sections, longitudinal profiles, and maps.

Part 6: Channel Description

This part has six topics that the analyst can use to characterize the channel in terms of its dimensions, flow regime, and geologic, sedimentary, or engineered controls on bed scour and bank retreat. This supplies the basic data collection outline the analyst will need to describe and define fluvial hydraulics, boundary conditions, and potential for instability.

Dimensions: record the size and shape of the channel using standard parameters of hydraulic geometry, such as average top bank and water surface widths, average channel and water depths, reach slope, estimated mean velocity, and Manning's "n" flow resistance coefficient for in-bank flows. (Measurements do not need to be detailed or precise, but they must adequately represent the channel. The analyst should take care when selecting measurement points to ensure that the results are generally typical of channel dimensions; this may require measuring selected locations, for example, a bend apex and a crossing in a meandering channel, and averaging the results to produce reach-representative values.)

Flow Type: record the flow regime in the channel according to the principles of free surface flow. (Uniform/tranquil flow is fully turbulent, sub-critical [Froude number less than one] and approximately uniform [water and bed slopes are roughly parallel and flow velocity varies little with distance along the channel]. Uniform/rapid flow also lacks major changes in flow velocity along the channel, but is super-critical [Froude number greater than 1]. Pools and riffles are undulations in the channel bed that produce non-uniformity of flow; during low-flow, pools are areas of deep, slower than average flow velocities and of a gentler water surface slope; riffles are bar-like features with shallow, faster than average flow velocities and—at base flow—have a steep, tumbling water surface slope. Steep and tumbling flow occurs in high gradient streams—generally gradients steeper than 1%—with coarse bed material that disrupts the water surface and produces locally super-critical flow between, around, and over the boulders. Steep and step-pool flow is found in steep channels with gradients steeper than 10% where boulders are arranged in periodic steps across the channel with plunge pools in between.) (See Bathurst [1997] for a detailed discussion of fluvial hydraulics.)

Bed Control Types: define the composition of any bed controls, such as bedrock outcrops, boulders, cohesive materials, artificial structures, and weir-type jams formed by woody debris.

Bed Control Frequency: identify levels of limits to vertical incision due to local geology, bed materials, and/or engineering structures. (A control is a feature which cannot easily be eroded by the river, which prevents continued incision, sets the bed elevation, and controls the shape of the backwater curve upstream.

Width Control Types**:** define the type of width controls (if any), such as bedrock outcrops, cohesive materials, and deflector-type jams formed by woody debris. (Controls due to fine sediments are often associated with clay plugs and bank-swamp deposits in the floodplain left by earlier lateral channel activity.)

Width Control Frequency: identify limits (if any) on the degree of widening and/or lateral migration allowed by the local geology, floodplain alluvium, and/or man-made structures. (A control is a feature which is not easily eroded or by-passed by the river, which prevents continued bankline retreat and thereby reduces or redirects channel shifting or enlargement trends.

Part 7: Bed Sediment Description

This part has ten topics that the analyst can use to characterize channel bed sediments by their composition, stratigraphy, depth, size distribution, and bedforms; and to describe bar types and their materials; in order be able to estimate bed material mobility and transport rate, and to be able to gage the potential for bed instability.

Bed Material: qualitatively describe the bed sediment. (There are fundamental differences in the fluvial processes, hydraulic geometries, and types of sediment-related problems found in rivers with clay, silt, sand, gravel, and boulder beds. Bed material properties usually vary with position in the channel, so special care must be taken to carefully observe the bed at selected locations [e.g., bends and crossings in a meandering stream] before completing this topic. While quantitative measurements of bed sediment are usually desirable [and covered in this section], they are not always feasible, in which case a qualitative description may have to suffice.)

Bed Armor: identify whether or not a coarse surface layer is present. (Both armor layers tend to reduce differences in the mobility of particles of different sizes, reduce the availability of finer, substrate sediments for transport, and reduce the potential for bed scour; static armor is much coarser than the underlying sediment and is immobile under all but catastrophic flows; mobile armor is coarser than the underlying substrate sediment and can be transported by moderate events below bankfull flow.)

Sediment Depth: record the depth of loose sediment in the channel bed. (This gives a guide to the size of the reservoir of sediment stored in the channel that is potentially available for transport; the depth of loose sediment can indicate the thickness of the active layer and is also a useful indicator of the status of vertical stability in the channel: degrading channels have a thin layer of [or no] loose bed sediment, while aggrading channels usually have a great depth of loose sediment in the bed.

Surface Size Data and Substrate Size Data: quantitatively describe bed materials based on sieve-by-weight or size-by-number analyses of samples taken from representative locations; a separate substrate sample is only necessary if an armor layer is present. (Techniques for sampling and analyzing bed sediments are described in most rivers textbooks. It may not always be necessary to measure bed material sizes quantitatively. A qualitative description [see **Bed Material**] may be sufficient, depending on the objectives of the CMZ study.)

Bed Forms (Sand): record the presence (if any), type (ripples, dunes) and height of bed forms in sand-bed channels. (Bed forms produce roughness, which increases the Mannings "n" for the channel, in addition to the roughness associated with grain size; they may also play a prominent role in bedload movement, but bedforms on this scale are not usually present in gravel-bed rivers.)

Bars: mark the frequency of mid-channel bars. (Bars account for macro-scale bed features and the presence of divided flow; they can have important impacts on flow resistance, flow conveyance and sediment transport capacity because divided flows are generally less hydraulically efficient than single-channel flows; they also provide important sites for in-channel sediment storage, as well as provide valuable habitat diversity.)

Bar Types: describe the shape (morphology) of any bars. (Bars are major features of the bed topography and they are intimately related to the distributions of primary isovels, secondary velocities and sediment transport; depending on their shape, bars may be responsible for deflection of flow that preferentially erodes one or both banks and thereby promotes bankline retreat.)

Bar Surface Data *and* ***Bar Substrate Data:*** quantitatively describe bar material based on sieve-by-weight or size-by-number analyses of samples taken from a representative area of the bar; if a single sampling location is used, this should be at about mid-bar; detailed sedimentary studies should include additional samples that represent the bar-head and bar-tail materials, but a separate substrate sample is only necessary if an armor layer is present. (Bars are often the primary source of sediment for transport, especially in rivers with armored beds; bar samples may be used to indicate the approximate size distribution of the sediment load and as input data for an appropriate sediment transport equation.)

Channel Sketch Map *and* ***Representative Cross-Section:*** visually represent the channel in the study reach in these two spaces by documenting forms and features of the active channel(s) and channel features—such as secondary channels—not readily seen from the aerial photograph record, and recording the locations of sampling points for bed and bar sediment samples and cross-sections (**Figure B-5**). Photographs should also be taken to show (1) upstream and downstream views along the study reach, (2) the right and left banks, and (3) any special features of the channel. Photograph points and orientations should be marked on the sketch map so that where photographs were taken can be located and they can accurately be retaken in any future surveys. This greatly enhances their value as a guide to channel changes, such as bank erosion or vegetation succession. (See **Section 4.2.4** of the main document for more information.)

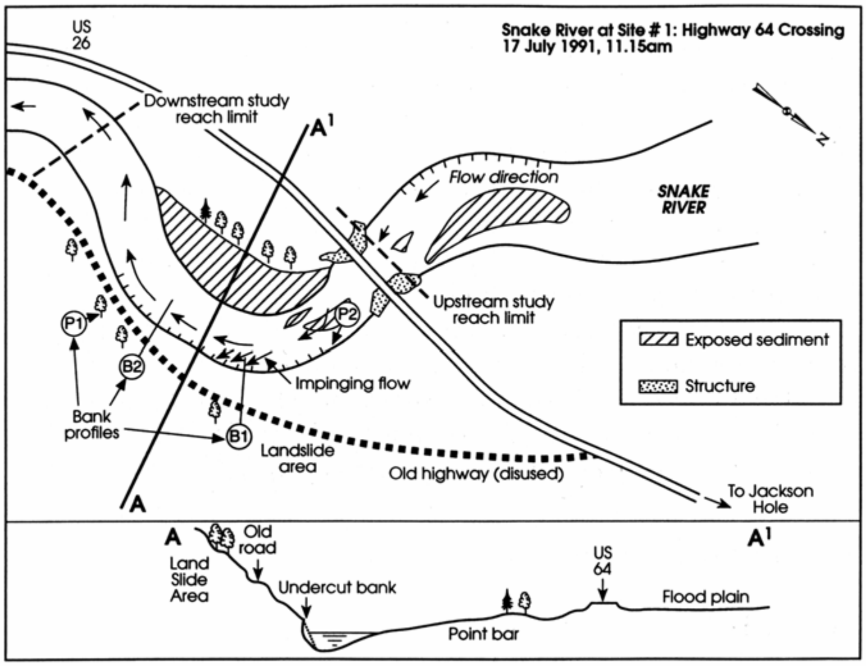

Figure B-5. Example sketch map and representative cross-section (Thorne 1998).

B.2.4 Section 4 – Left Bank Survey *and* Section 5 – Right Bank Survey

These two sections deal in greater detail with geomorphic aspects of the left and right banks (respectively) of the study channel and allow the analyst to provide a complete record of the banks in terms of their characteristic geometry and materials, vegetation, erosion and accretion processes, and geotechnical failures.

It is important that the analyst completes each part in each section independently of the information gathered in other parts. For example, the status of bank stability with regard to mass failure is not addressed until the fourth part (**Bank Geotechnical Failures**) of each section, so the analyst should not allow the presence or absence of slope failures to influence choices in the first three parts of each section, which do not deal with bank failures, but with other bank characteristics and bank erosion processes.

Comprehensive evaluations of both banks and their dynamics are critically important for accurate CMZ delineation because they form the basis for explaining planform evolution and bankline movement; they also supply practical information that the analyst can use to select appropriate models in anticipation of future bank adjustments (see **Section 3, Channel Movement** of the main document). **Section 4 – Left Bank Survey** and **Section 5 – Right Bank Survey** can also be used to evaluate actively eroding terraces or terraces susceptible to channel erosion.

Section 5 – Right Bank Survey consists of **Part 12** through **Part 15**, which are identical to **Part 8** through **Part 11** in **Section 4 – Left Bank Survey**.

Part 8 and Part 12: Bank Characteristics

This part contains nine topics that the analyst can use to characterize the bank in terms of its type, materials, protection status, approximate dimensions, shape, and degree of cracking. All of these characteristics are fundamentally related to bank erodibility, stability, management, and protection.

Type: classify the bank on the basis of its material properties—non-cohesive, cohesive, uniform, or layered. (There are important contrasts between banks formed in different materials or combinations of materials: non-cohesive banks are formed in sands, gravels, cobble, and boulders that lack intrinsic cohesion; cohesive banks contain silts and clays which give the bank some intrinsic cohesion; uniform banks are composed of a single layer of similar materials that are cohesive or non-cohesive; layered banks consist of layers of non-cohesive and cohesive materials that were deposited during present or past aggradational phases—they are often of uneven thickness, which can have significant meaning to bank erosion and hydrology.

Protection Status: establish whether or not the bank has been stabilized by man-made revetments or structures; if a bank has been artificially stabilized, the condition and effectiveness of the structure should be described in the **Notes and Comments** space.

Bank Materials: indicate details of the composition of bank materials for up to four layers within the bank. (This information supports interpretations of bank erodibility, stability, and sediment supply to the fluvial system. For example, the occurrence of a weak layer close to the top of a layered bank may not matter, but the same layer located at the toe could allow rapid undercutting and/or piping to generate a mass failure of the overlying layers.)

Layer Thickness: record the thickness of each stratigraphic unit that makes up the bank. (Layer thickness is significant to bank hydrology and stability because, for example, a cohesive bank with thin layers of sand may be susceptible to piping failure due to concentrated seepage in the permeable layers [Hagerty 1991a, 1991b].)

Bank Profile Shape: augment height and slope data by specifying the form of the bank profile. (The profile of the bank can be a good indicator of the recent history of bankline retreat, stability, or advance. Some typical bank profiles and their geomorphic interpretations are shown in **Figure B-6**.)

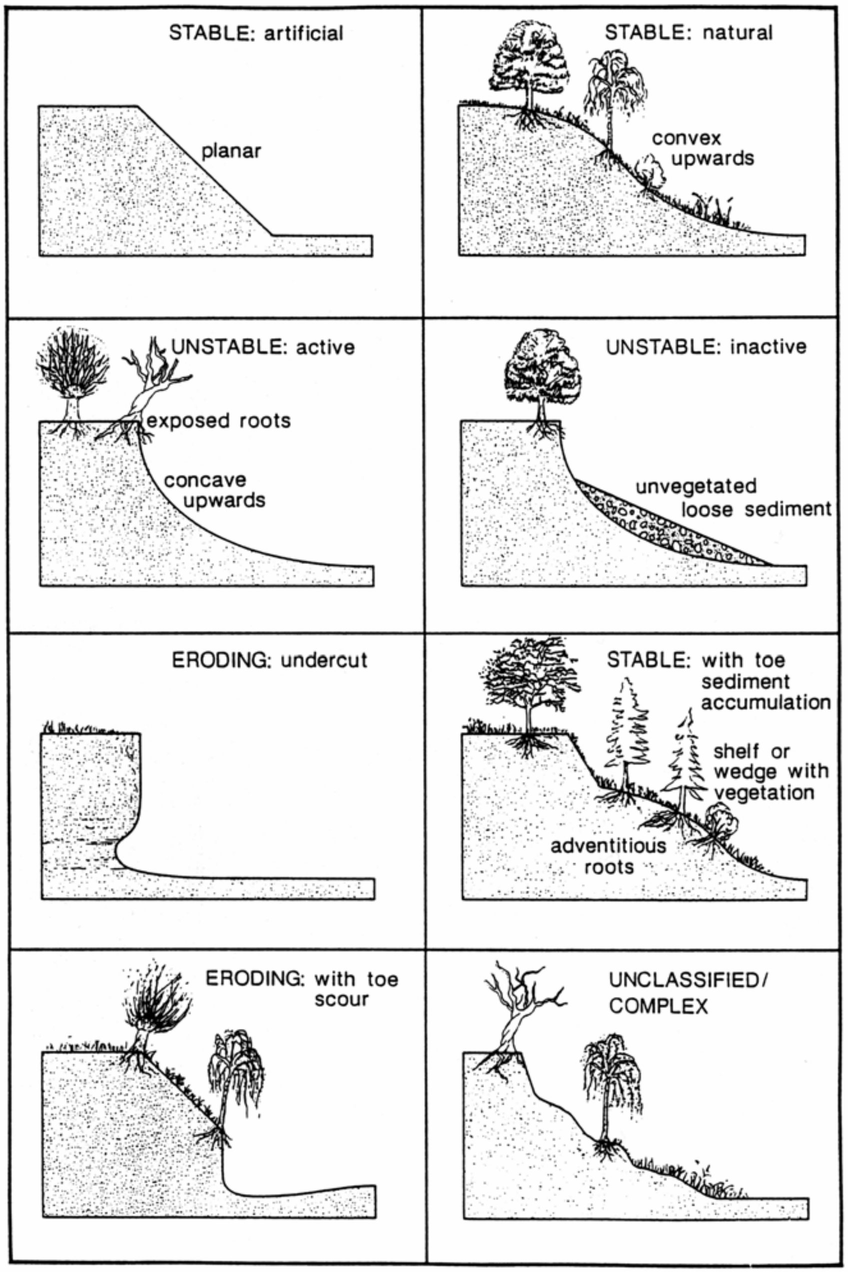

Figure B-6. Classification and geomorphic interpretation of typical bank profiles (Thorne 1998).

Average Bank Height** and **Average Bank Slope: record representative values for the overall height and steepness of the bank, both of which are important for determining stability with respect to mass failure.

Tension Cracks: note whether tension cracks are present behind the bankline. (Cracks develop vertically downwards from the ground surface behind steep banks due to horizontal tensile stresses in the soil; they greatly reduce the stability of the bank with respect to mass failure: the presence of a tension crack indicates that the bank has already failed and may be close to collapse.)

Crack Depth: record the depth of tension cracking as a proportion of the total bank height; cracks rarely exceed a depth of half the total bank height.

Part 9 and Part 13: Bank Face Vegetation

This part has twelve topics that the analyst can use to characterize vegetation in the study area. The importance of bank vegetation's affect on bank morphology, erodibility, and stability is recognized by both engineers and geomorphologists, therefore vegetation is covered in some detail in the reconnaissance.

Vegetation*:* broadly classify the types of vegetation found on the bank face. (Vegetation may benefit or be a detriment to bank stability depending on the nature of the vegetation and the geomorphic environment; also, variation in the type of vegetation with respect to height on the bank profile can be a useful indicator of bankfull elevation.)

Orientation: record the angle at which the trunks of trees growing on the bank are leaning over. (Trees naturally grow vertically and vertical trunks generally indicate bank stability; trees leaning towards the channel, on the other hand, are an indicator of wind-throw and/or bank instability; additionally, trees with curved trunks indicate past bank instability which led to leaning, but not toppling of the trees. The date of past bank instability can be estimated by tree coring [dendrochronology].)

Tree Types: mark the presence (if any) of any trees. (Deciduous and coniferous trees affect bank stability in different ways; compared to deciduous trees, conifers are shallow-rooted and lack a vegetative under-story; for this reason, deciduous trees can be more effective than conifers in helping to stabilize a bank.)

Tree Species: record the particular species of any trees present. (Different trees display different growth patterns, biomasses and physiographies, which means they produce different degrees of erosion protection and root reinforcement, while exhibiting contrasts in flood tolerance and vulnerability to wind-throw; tree identification is therefore an important step towards interpreting bank form, stability, and susceptibility to retreat.)

Density and Spacing: describe the intensity and pattern of vegetative cover (if any) on the bank face. (Density refers to the intensity with which plant stems are packed together: the higher the density of the vegetation, the better the erosion protection it provides by increasing effective roughness (n value) with respect to height and flow resistance; Spacing describes how the vegetation is spread over the bank: widely spaced clumps with gaps have a greater potential for erosion than closely spaced clumps or a continuous cover of plant stems.)

Roots: define the relationship between the vegetation roots and the bank surface. (If the bank face is stable, then the roots are normally found below the soil surface, but if sediment is accumulating on the bank, vegetation will produce adventitious roots above the original root collar, which will then grow into the new sediment as the ground rises relative to the plant. Additionally, if the bank face is eroding, plant roots are exposed as the ground surface retreats relative to the plant: if erosion is rapid, then roots will poke straight out of the bank face; if erosion is slow, the exposed roots will tend to curve and grow back into the bank face. Hence the configuration of the roots can be used to infer past and present trends and rates of bank face accretion or erosion.)

Location: define the position of the vegetation on the bank profile. (Vegetation at the bank top is useful in preventing subaerial erosion, but is less effective in helping to stabilize the bank with respect to mass failure than if it is located lower on the bank; this is because (1) trees low on the bank are less exposed and are less vulnerable to windthrow, (2) closely spaced trees low on the bank may have a buttressing effect, and (3) vegetation low on the bank reduces near-bank velocities, particularly at the bank toe. Additionally, vegetation on the bank face increases overall channel flow resistance: recent research suggests this significantly lowers in-channel conveyance on channels of low—less than about 10—width-to-depth ratios [Masterman and Thorne 1992, 1993; Darby and Thorne 1996b].)

Diversity: record the mixture of vegetative types present on the bank. (Diversity increases with the age of the riparian ecosystem. Generally, a mature assemblage with a wide variety of species and types is more robust and better able to resist erosion than is a monostand of a single plant type. Climax vegetation is a mature ecosystem in which there is no longer any succession of plant species with time.)

Health: note the state of the vegetation. (Dead or dying vegetation can be a serious liability to bank stability: it is vulnerable to wind-throw, drags down the bank, and if LWD falls into the channel it may divert flow and cause bed scour and bank erosion. LWD can also have a positive effect by creating flow-retarding jams that stabilize channels, store sediment, and create habitat.)

Age: note the age of the vegetation. (This can be a useful guide for evaluating the geomorphic history of the bank: mature vegetation can only develop on a stable bank, while a predominance of young, immature vegetation hints at recent instability. Although vegetation age can be estimated by eye, it can more accurately ascertained by counting annual rings (dendrochronology), which requires both tree-coring tools and personnel with the necessary expertise. Additionally, fallen trees that have not died will produce new stems that grow vertically upwards from the downed trunk; breaking off one of these stems and counting its annual rings is a good way to gage elapsed time since the failure that caused the tree to fall.)

Height: note the general height of vegetation; the height may be noted qualitatively, but space on the sheet is also provided for a numerical value, if necessary. (Height is a factor in determining the possible effects of vegetation dragging down the bank and thereby impeding near-bank flow in the channel: tall trees, particularly on the upper bank or top bank, may drag down a section of bank by toppling into the channel due to either surcharge or wind-throw; tall, flexible vegetation has a higher effective roughness height and can produce flow resistance in low width/depth ratio channels [Darby and Thorne 1996a].)

Lateral Extent: describe the width normal to the bankline of the band of bank vegetation, which refers to how extensive the band is in relation to the riparian corridor. (A wide, extensive band of vegetation along the bank protects the floodplain from grazing and trampling by animals and damage by people; a wide band has many advantages to the bank's environment, habitat value and aesthetic appearance as well as its stability. A narrow band or single line of trees can be grazed on the bankward side, which can produce asymmetrical trees and bushes that lean over into the channel and are vulnerable to collapse and wind-throw.)

Bank Profile Sketches: visually represent the left or right bank in the study reach (see **Figure B-7** for an example) by recording characteristic slope profiles, geotechnical features and sedimentary layers, engineered structures, and the locations of any sediment sampling points in different bank layers. Photograph points and orientations should be marked on the sketch map in **Section 3** so that where photographs were taken can be located and retaken in any future surveys. This greatly enhances their value as a guide to channel changes, such as bank erosion or vegetation succession. (See **Section 4.2.4** of the main document for more information.)

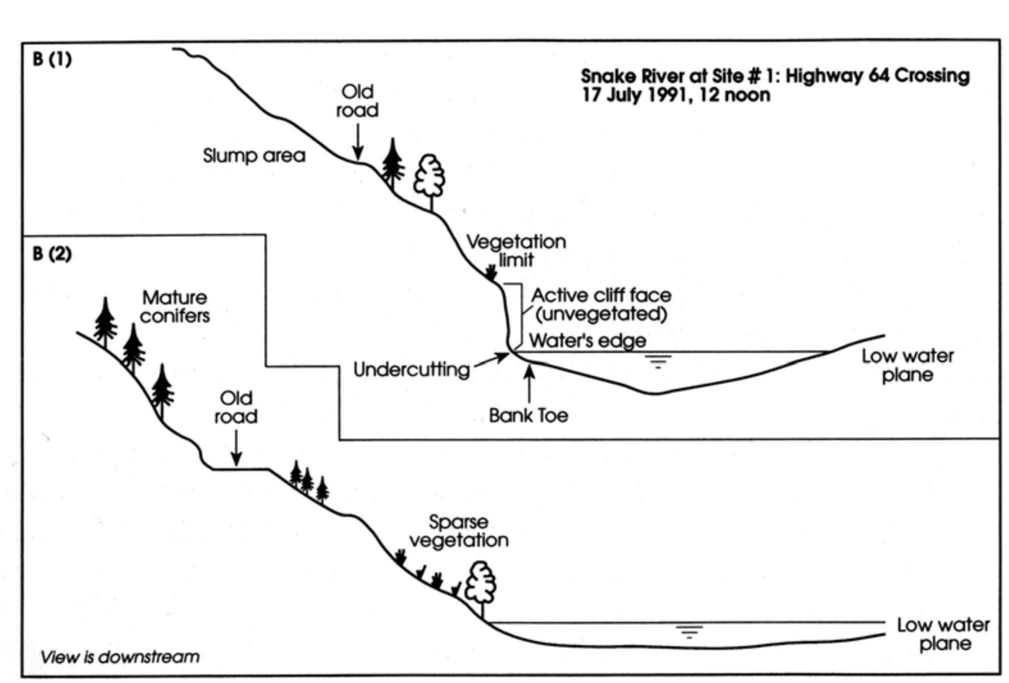

Figure B-7. Example of a bank profile sketch (Thorne 1998).

Part 10 and Part 14: Bank Erosion and Shoreline Accretion

This part has seven topics that the analyst can use to document the processes responsible for erosion and its distribution over the bank—both along the channel and in the bank profile. Almost half of this part is interpretative, so the analyst must have some background understanding of bank erosion to complete this part of the survey.

Erosion Location: establish the position of the eroding area of the bank in relation to major features of the channel. (A spatial association between the area of erosion and a channel feature is not necessarily causal, but it is still important to record the relative position of bank erosion in relation to channel planform, bed features, and engineering structures.)

Present Status: establish the condition of the bank at the time of observation; it may be intact—that is, not affected by erosion. (If, as is usual, the survey is made at low-flow, it may well be that the bank is eroding, but not actually at the time of observation, and is considered to be dormant; if erosion is actually occurring at the time of the survey, then it is considered to be active. Similarly, a bank advancing through deposition may be either dormant or active at the time of observation.)

Rate of Retreat *and* ***Rate of Advance:*** record the speed of bankline migration, if it can be determined. (The rate of retreat or advance may be determined in the office from historical maps or aerial photographs [see **Section 4.1** of the main document], on-site from surveys re-taken over time, or indirectly from discussion with local landowners and other involed parties. Although potentially valuable, landowners' opinions and other anecdotal evidence must of course be treated with caution and should not be accepted without independent corroboration.)

Interpretive Observations: these three topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Extent of Erosion: define the scale of bank erosion within the river system; this is usually an essential step towards identification of the underlying cause of a bank erosion problem; for example, if a problem is common to the whole fluvial system, then a local cause is unlikely.

Severity of Erosion: determine the level of significance of any erosion problem. (All alluvial rivers display some bank erosion as part of their natural, geomorphic evolution.)

Processes: identify the processes responsible for bank erosion. (Evidence of parallel flow erosion—the detachment and removal of intact grains or aggregates of grains from the bank face by flow along the bank—includes [1] the observation of high-flow velocities close to the bank, [2] near-bank scouring of the bed, [3] undercutting of the toe/lower bank relative to the bank top, [4] a fresh, ragged appearance to the bank face, and [6] the absence of vegetation on the bank face. Evidence of impinging flow erosion—the detachment and removal of grains or aggregates of grains by flow that erodes the bank at an oblique angle to the long-stream direction—includes [1] the location of the thalweg at an oblique angle to bank, [2] high-flow velocities that approach the bank at an oblique angle, [3] braid bars, or other bars, that direct the flow towards the bank, [4] tight, short-radius meander bends, [5] strong eddying adjacent to the bank, [6] near-bank scouring of the bed, [7] undercutting of the bank face, and [8] the absence of vegetation on the bank face. Impinging flow occurs in braided channels where braid bars direct the flow strongly against the banks, in meander bends where the radius of curvature of the outer bank is less than that of the channel centerline, and at other locations where an in-stream bar or obstruction deflects and disrupts the flow of water.)

Other: There may be other erosion processes, such as trampling by stock, damage by anglers, etc. that may need to be noted; if some other erosive process is observed in the field, this box should be marked and the name of the process written in below.

Part 11 and Part 15: Bank Geotechnical Failures

This part has five topics that the analyst can use to identify any geotechnical instability and note its distribution over the bank.

Failure Location: note the position of the failing area in relation to major channel features. (A spatial association between a bank failure and a channel feature is not necessarily causal, but it is still important to record the relative position of bank collapse in relation to channel planform, bed features, and engineering structures. Failures usually coincide with the location of bank erosion, but this may not always be the case; where instability is the result of processes operating within the bank, the failure may be located away from the areas of active fluvial erosion.)

Present Status*:* note the condition of the bank at the time of observation. It may be stable—that is, not affected by geotechnical instability and showing no evidence of past failures. (If the bank appears to be stable, but shows evidence of recent failures, there is the possibility they might recur in the future. Under these circumstances failures tend to occur during or soon after high-flow stages in the channel. If the survey is performed during low-flow conditions and there has not been heavy rain or snowmelt for some time, the bank is potentially unstable, but stable at the time of observation. Such a bank is considered unstable, but dormant because it would likely fail if saturated and/or during rapid draw-down conditions. If failures recently occurred or are observed during stream reconnaissance, then the bank is unstable and active.

Failure Scars and Blocks*:* note the presence and appearance of these two prominent features produced by bank instability. (Scars are the failure surfaces created in the bank when a block of material falls, slumps or slides away. Blocks are the more or less intact pieces of the failure mass which come to rest at the bank toe, or on the lower bank. Immediately after failure, the scars and blocks are fresh with sharp edges, but weathering softens their appearance as time passes. The appearance of the scars and blocks gives an indication of the time elapsed since they were created.)

Interpretive Observations: these two topics are interpretative rather than objective, which means the analyst will have to use some degree of subjectivity. Space is therefore provided for the analyst to mark a level of confidence in the interpretations.

Instability—Severity: put any instability into perspective. (While nearly all rivers display some bank instability as part of natural geomorphic evolution, not all bank instability poses a problem that merits detailed analysis.)

Instability–Extent: define the scale of bank instability within the river system; this is usually an essential step towards identification of the underlying cause of a bank stability problem; for example, if a problem is common to the whole fluvial system, then a local cause is unlikely.

Appendix C: Probabilistic Analysis of Channel Location

Graf (2000) developed a method for estimating the probability of erosion hazards using geomorphic parameters within a GIS platform. His approach relies on three basic steps:

1. scanning and registering remote sensing data into GIS;
2. digitizing channel features as polygons for each data set; and
3. subjecting each map to areal analysis by assigning erosion values (based on the channel's locations in the historical record) to each cell or pixel.

Mapping channel features is limited to the geomorphic surfaces that are consistently identifiable between each data set. At a minimum, the active channel and secondary channels should be mapped over time (at least 50 years). However, the investigator can use stereo-pairs of sufficient resolution to digitize bars, islands, the low-flow channel, man-made structures, and terraces. (*Note:* Although mapping these additional channel features can be useful for estimating the effects of causal mechanisms on channel migration, field visits are essential for educating the investigator on the appearance and common occurrence of each type of channel feature identified on aerial photographs.) For each data set, feature mapping produces a GIS vector file that defines the boundaries of channel forms as polygons. Vectors files are converted to raster files in order to create a final feature map for each year of analysis. After this step is complete, the analyst will have a series of maps for the study area that show channel forms over the study period. The analyst can then calculate areal changes of channel features over time and plot them on a stacked diagram (**Figure C-1**).

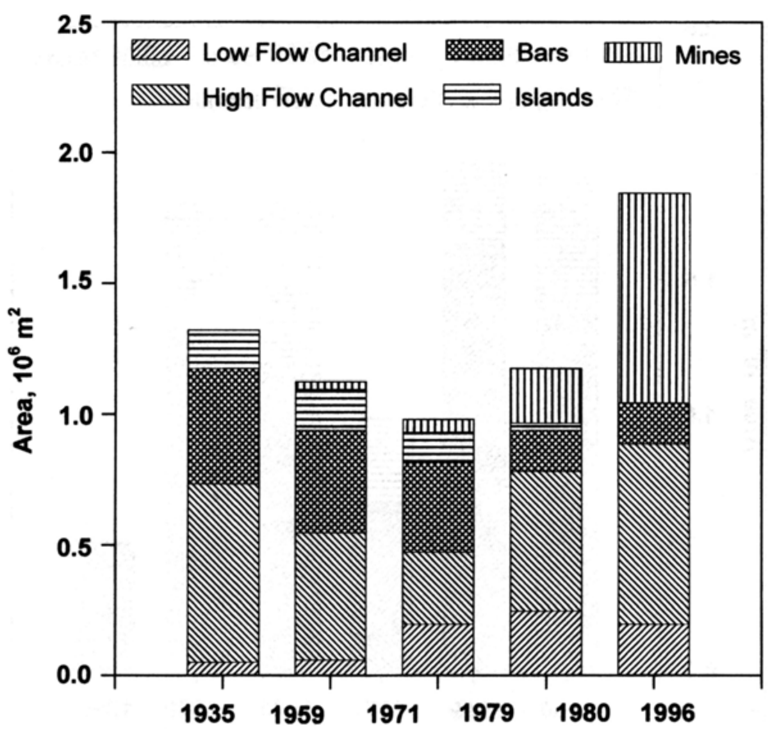

Figure C-1. A stacked bar diagram showing the history of areal changes in geomorphic channel forms (Graf 2000).

The next step is creating a locational probability map of the active channel for each channel reach in the study area (**Figure C-2**). Each map consists of cells, or pixels, that correspond to the raster components of the GIS image that was created from aerial photographs. Each pixel has a value between 0 and 100 that is based on a random sampling of empirically-derived selections of the observed past record and that represents the probability that the active channel occurred within that pixel during the time period of study. In other words, if a pixel has a value of 100, there is a 100% probability that the active channel occupies that pixel during any randomly selected time over the study period. If the pixel has a locational probability of 50%, then the active channel occupies that pixel in half of the cases of a series of randomly selected times (Graf 2000).

The process for creating the probability map begins with the earliest raster image that shows distribution of the channel features of interest. Within GIS, the pixels in all maps are converted to values of either 0 or 1, which indicate the absence or presence of the active channel. The following algebraic expression summarizes the locational probability of a given feature, such as the active channel, for each pixel in the final map:

$$p = (W_1F_1) + (W_2F_2) + \ldots (W_nF_n)$$

such that:

$$\sum (W_n) = 1.00$$

where p is the final locational probability for the pixel of a feature F, F_n is the feature occurrence for the pixel in map n, equal to either 1 for occurrence or 0 for none, n is the number of aerial photos or map coverages for the study site, and W_n is the weighting value assigned to each map n, determined by one of the two following methods.

In the first method, the length of time represented by the map is the control on weighting:

$$W_n = t_n/m$$

where W_n is the weighting value assigned to map n, m is the total number of years in the photographic record, and t_n is the total number of years represented by map n.

In the second method, the weighting value depends on the number of event-driven change episodes as shown by the entire photographic record where each map shows the conditions after a flood:

$$W_n = 1.00/x$$

where W_n is the weighting value assigned to map n, and x is the total number of maps, with each showing the results of a different flood (**Figure C-3**).

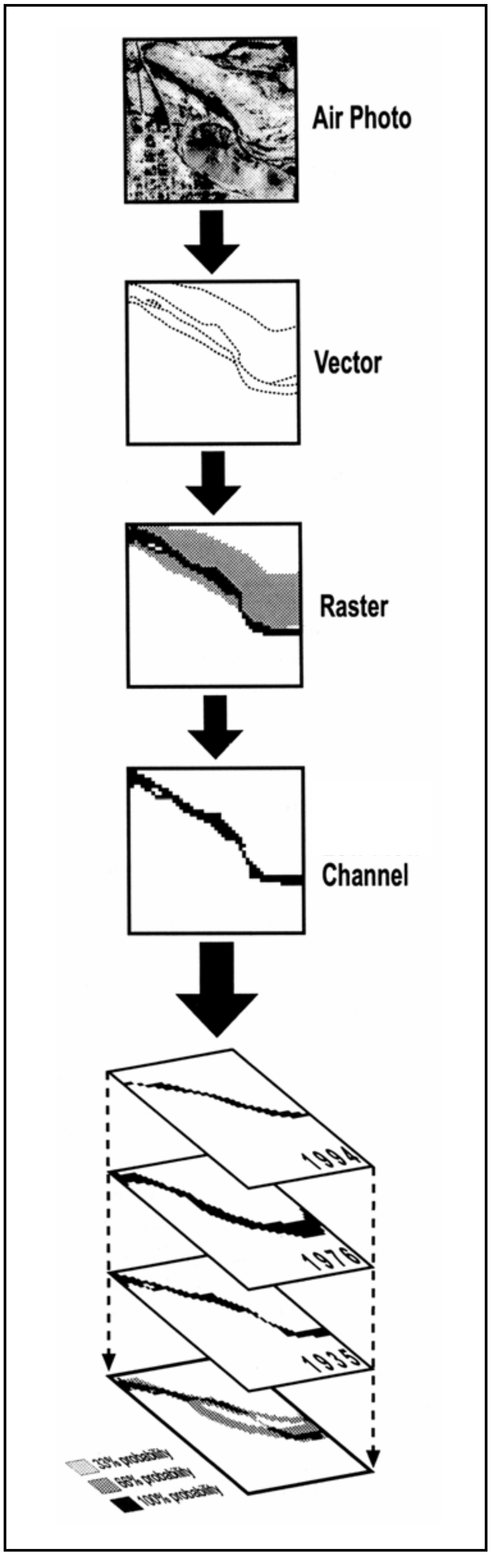

Figure C-2. Schematic summary of aerial photographs being converted to a locational probability map (adapted from Graf 2000).

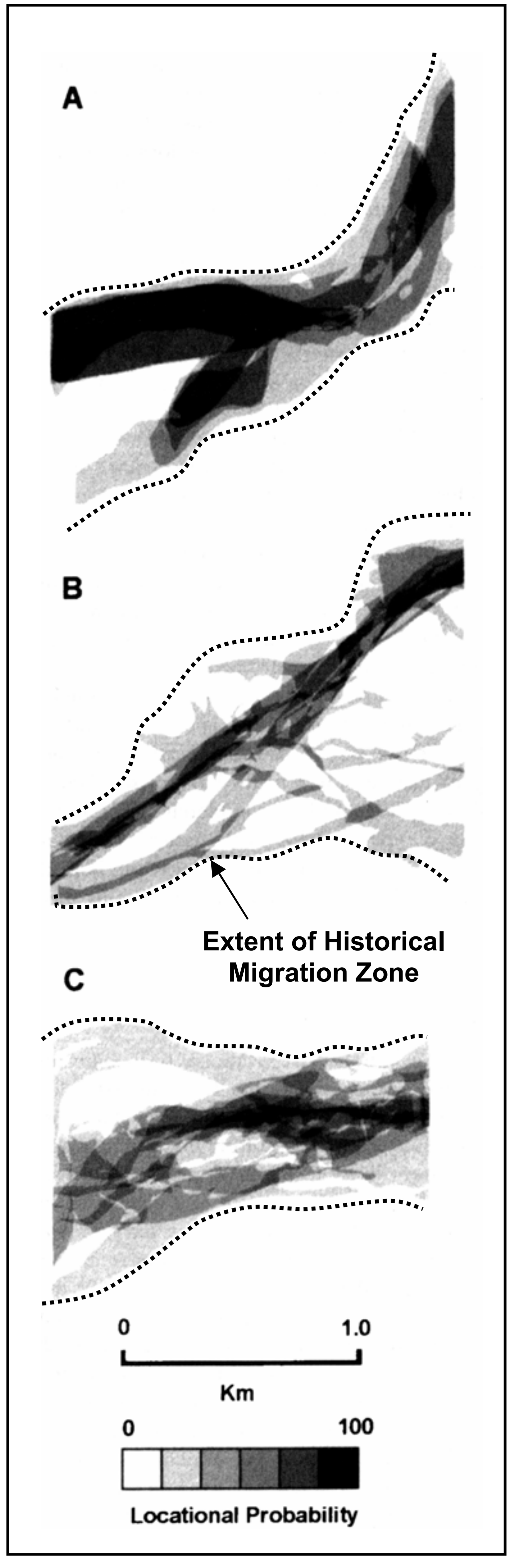

Figure C-3. Three locational probability maps that use the event-driven weighting process. The HMZ is the outermost extent of historical channel locations, or the outermost extent of locational probability (adapted from Graf 2000).

Advantages
This approach incorporates locational probability into the historical analysis and shows the spatial distribution of erosion probabilities within the HMZ. The outermost line indicating a zero probability of erosion can be used as the HMZ boundary.

Graf (2000) uses process-based measurements of fluvial features to define changes in channel dynamics over time. By using polygons in GIS, this method captures greater detail than is possible using manually-based techniques, such as channel transects.

If access to GIS is not possible, the analyst can use channel transects, as outlined in Graf (1981), to manually estimate erosion probabilities.

Limitations
This approach may be inappropriate for evolving systems, given that it relies on past channel locations for predicting the likelihood of future channel occupation. If the analyst can demonstrate that the HMZ equals the CMZ (because future trends in channel behavior are captured in the historical record), then this approach provides a user-friendly method for initially calculating erosion risk. Otherwise, refer to **Delineating the Channel Migration Zone** (**Section 4** of the main document).

For more information on limitations to this approach, refer to **Limitations of Planimetric Analysis** in **Section 4.1** of the main document.

Appendix D: Sources of Information

Sources of information include historical and contemporary documents, and data that is useful for reconstructing past channel conditions and assessing channel change over the study period. In many cases, information already exists on the processes and rates of channel erosion either in the study area or in similar systems. Information on similar systems can be useful for identifying factors that may control rates and patterns of channel movement, and for identifying the relative importance of processes. Historical information may be in the form of surveys, maps, government reports, or photographs. Contemporary information may include published literature, agency records, engineering and geotechnical reports, local theses and dissertations, or anecdotal information from residents or others interested in the area. Background information and planimetric analyses are significant aids for prioritizing fieldwork and specifying fieldwork goals. It also helps to note missing information at an early stage so that it can be accounted for in fieldwork plans (Reid and Dunne 1996).

The following is a list of potential sources of information that are useful in a CMZ study. The sources listed below are ranked as essential (necessary to do the study) **(E)** or best to use if available **(B)**. Unranked sources are useful, but not essential. (Appendix C provides contact information for some of the historical and contemporary data listed below.)

Remote Sensing

- **(E)** Aerial photographs, beginning in the 1930s: the most useful scales for photo analysis are larger than 1:24,000 (e.g., 1:10,000). It is important to use photos as far back as they are available; decadal coverage is ideal and, if possible, all data sets should have similar spatial scales to minimize error. Some published sources provide instruction for identifying and interpreting geomorphologic processes using aerial photographs: Jones and Keech (1966) describe the use of aerial photos in water erosion surveys; Emery (1975) discusses identification of sheetwash, gullies, and landslides; and Way (1978) provides a more general discussion on interpreting substrate properties and geomorphologic processes. Of special note: bank erosion and channel movement are most visible in early spring before deciduous trees have leafed out. Additionally, the visual appearance of a channel changes with discharge, therefore (if possible) it is important to note the discharge of the channel at the time the aerial photograph was taken.
- **(B)** Digital Elevation Models (DEMs): raster files consisting of individual pixels, each of which represents a specific position on the earth's surface. DEMs are typically referred to by the size of the pixels within the file. For example, each pixel in a 30 m DEM is 30 m on each side; the smaller the pixel size, the more precise the DEM. In addition to a specific set of earth coordinates, each pixel has an elevation, usually given in a Universal Transverse Mercator (UTM) projection (meters north of the equator and meters east of the 180th meridian). Pixel elevations theoretically represent the average elevation of the pixel. For example, the elevations in a 30 m DEM each represent the average elevation of a 900 m^2 area. A slope map derived from a DEM not only gives an idea of embankments that limit channel movement, but can also be used to determine the relief captured by the DEM pixel size. For

example, a 20% slope on a 30 m DEM corresponds to a 6 m rise between two orthogonal pixels, and a 30% slope corresponds to a 9 m rise been the two pixels. Although DEMs can be used to quickly differentiate the valley bottom from adjacent hillslopes, the resolution of the DEM will influence the accuracy of a preliminary delineation of the valley bottom (Zhang and Montgomery 1994). DEMs are readily analyzed using GIS software, such as ESRI's ARC VIEW Spatial Analyst Extension, and can provide a valuable tool for delineating a CMZ. Accordingly, use of DEMs for CMZ delineation requires someone with terrain modeling experience and an understanding of the limitations of these datasets. 10 m DEMs are preferred over 30 mDEMs (Zhang and Montgomery 1994) for delineating the Holocene valley bottom and past channel locations. 30 m DEMs are available for all of Washington State; 10 m DEMs are currently available for most of western Washington.

- **(B)** Light Detection and Ranging (LiDAR) data: provides excellent topographic information for determining the Holocene valley bottom and historical locations of the stream channel. Within the context of this report, LiDAR refers to the range finder type of LiDAR data, which measures the distance from the LiDAR instrument to the target (the earth's surface). Maps developed from LiDAR have numerous advantages, including high-resolution topographic information in river valleys (e.g., 2 ft contours) that is not available from other mapping techniques. In addition to high resolution topographic data, LiDAR can be draped with other data (such as infrastructure, high resolution digital aerial photographs, field survey transects, or any other spatially referenced data) for historical or current conditions. Furthermore, if physically revisiting the field is not an option or is not cost effective, the analyst can virtually revisit the field with the added advantage of being able to pause to query the datasets. LiDAR processing is a complex task requiring considerable expertise, especially when the analyst is creating a reliable bare earth model (required for most fluvial geomorphic applications). If LiDAR originates from an external source, the metadata should be complete (including error reports), otherwise a thorough inspection of the data's quality should be conducted. Because current LiDAR technology does not allow for mapping of features under water, LiDAR missions are best flown during low flow conditions. Although not absolutely necessary for CMZ delineation, LiDAR data provides the best means currently available for mapping channel and floodplain features and should be utilized whenever it is available.
- **(B)** Orthophotos (Department of Natural Resources): aerial photographs in which the image displacements caused by camera tilt and terrain relief have been removed. Orthophotos are available in digital and hardcopy.
- State and County GIS resources (Department of Ecology, Department of Natural Resources). Often state or county staff have GIS data layers that can be used as base maps and refined for the purposes of the CMZ study:
  - **(E)** Bank hardening and revetment—provides information on the locations and extent of bank hardening efforts and contributes to the delineation of DMAs.
  - **(E)** Infrastructure—allows the analyst to interpret where private structures, highways, and county roads are at risk of erosion.
  - **(E)** Land use—provides context for changes to hydrology and other catchment or reach scale issues.
  - **(E)** Soils—offers data on the types of soils found on valley bottom surfaces.

- **(E)** Geology—supplies information on the erodibility of the valley bottom features and identifies other features, such as glacial deposits, alluvium, lacustrine deposits, bedrock, and landslides. If this data is available at adequate resolutions, it can be used to augment field work.
- **(B)** Vegetation layer—provides general information on vegetative communities so the analyst can evaluate the stability of terrace and floodplain banks.

Maps

- **(E)** U.S. Geological Survey (USGS) topographic maps (beginning in the 1890s).
- **(E)** Geology maps (USGS, state resource agencies).
- **(E)** Soils maps (USDA-NRCS, county soil survey maps).
- **(E)** Map of land ownership: aids in identification of stakeholders so the analyst can acquire permission to access the project area.
- **(B)** Government land survey records. The General Land Office (GLO) conducted its cadastral survey of Washington State circa 1850 and 1880. For the most part, these surveys predate floodplain logging, stream clearing, and widespread construction of sea or river dikes. GLO records are an essential source for characterizing riverine conditions prior to European settlement. Field notes are useful for reconstructing presettlement vegetation cover (e.g., Nelson et al. 1998; Radeloff et al. 1999); for characterizing riparian and valley bottom forests, including size and species of recruitable wood (Collins et al. 2002); and for mapping and characterizing riverine wetlands (North and Tevarsham 1984) and changes in channel widths (Knox 1977). GLO survey notes are discussed in more detail by Collins and Montgomery (2001).
- **(B)** U.S. Coast and Geodetic Survey (USC&GS) charts of the coastline and coastal rivers. These charts are generally to the upstream limit of navigation, and often a few tens of kilometers inland. In eastern Puget Sound, some early, less-detailed charts were made in the 1850s, with more detailed and accurate charts—at a scale of 1:10,000 or 1:20,000—made in the late 1870s to late 1880s. These charts were in most cases created after widespread tidewater diking (Collins and Montgomery 2001).

Reports

- **(B)** Watershed plans: urbanization, channel modifications, dams, effluent discharge, and streambed mining (e.g., from county governments, the Department of Ecology, hydropower companies, and gravel mining companies).
- **(B)** Annual Reports of the Chief of Engineers (U.S. War Department). In 1876, the U.S. War Department (predecessor to the U.S. Army Corps of Engineers) began filing annual reports on Washington rivers that described conditions mostly related to woody debris, which often completely blocked rivers to steamboat navigation. Beginning in 1880, engineers began clearing these log jams and snags; by the end of the decade they engaged in a regular program of *snagging* that continues to this day. Most of the annual reports on snagging and other river improvements include the number and size of removed snags (Collins and Montgomery 2001).
- Other Government reports (e.g., Nesbit et al. 1885; Magnum et al. 1911):
    - USGS
    - U.S. Army Corps of Engineers

- FEMA
- Federal Highway Administration
- County public works and natural resources departments
- State transportation and natural resources departments
- Published literature
- Agency records
- Studies contracted to engineering and geotechnical firms
- Local theses and dissertations
- Studies from areas with similar geology, climate, vegetation, and land use

Available Data

- **(E)** Streamflow data (flood events) (USGS gaging stations; see website: http://waterdata.usgs.gov/wa/nwis/nwis).
- **(B)** Cross-section and profile data from Army Corps of Engineers Flood Insurance Study maps.
- **(B)** Cross-section and profile data for assessing background changes in the channel bed elevation: FEMA Flood Insurance Study maps; archival data, such as Flood Insurance Studies (FIS) for FEMA; and USGS gaging stations. For example, Collins (1994) used FEMA FIS cross-sections of the Deschutes River to show a 2 m fluctuation between 1977 and 1993; Abbe (2000) documented 4 m of channel aggradation in Alta Creek between 1993 and 1994; and Stover and Montgomery (2001) found that 1.5 m of aggradation in the South Fork Skokomish River was due to an increase in sediment supply associated with logging and dam construction.
- Bridge and culvert as-built plans and maintenance records (county, state, and federal agencies).
- Rainfall records (NWS).
- Sedimentation data: bed and bank sediment size, transport rates, aggradation areas, and degradation areas (e.g., dam sedimentation records, consulting reports, USGS reports, and peer-reviewed journal articles).
- Water use data: irrigation, power generation, diversions, etc.
- Available hydraulic models (e.g., HEC-RAS, HEC-2, Mike 11, WinXSPro).
- Reservoir operation and sedimentation data.

Anecdotal Information

- Settlers accounts.
- Contemporary histories (e.g., Interstate Publishing Company 1906).
- Photographs (historical societies, library).
- Anecdotal information from residents or others involved in the area.

Appendix E: Sources for Historical and Contemporary Data

AERIAL PHOTOGRAPHY

United States Department of Agriculture: Aerial Photography Field Office
Website: http://www.apfo.usda.gov
Address: United States Department of Agriculture
Sales Branch
USDA FSA APFO
2222 West 2300 South
Salt Lake City UT 84119-2020
Phone: 801-975-3503
TDD: 801-975-3502
Fax: 801-975-3532
Highlights: Over 10,000,000 images, dating from 1955 to present.

United States National Archives and Records Administration
Website: http://www.archives.gov/research_room/obtain_copies/maps_and_aerial_photos.html
Address 1: Aerial Photographs Team
Cartographic and Architectural Reference (NWCS-Cartographic)
National Archives and Records Administration
8601 Adelphia Road
College Park MD 20740-6001
Address 2: National Archives and Records Administration
6125 Sand Point Way NE
Seattle WA 98115-7999
Phone: 206-526-6501
Fax: 206-526-6575
E-mail: seattle.archives@nara.gov
Highlights: Aerial photos from specific projects from all over the country.
Users can search on NAIL database for specific locations.
Holdings include Mount Baker project from 1928.

Washington State Department of Natural Resources: Division of Geology and Earth Resources
Washington Geoscience Resources: Special Materials
Website: http://www.wa.gov/dnr/htdocs/ger/specmate.htm#Aerial
Address: DNR Photo and Map Sales
PO Box 47031
Olympia WA 98504-7031
Phone: 360-902-1234
Hours: M-F, 8:30am-4pm
Highlights: Covers all counties in Washington State.
Most counties photographed beginning in the 1960s.

Washington State Department of Transportation
Website: http://www.wsdot.wa.gov/ppsc/aerial

Phone: 360-709-5550
Fax: 360-709-5599 (24 hours a day)
Hours: M-F, 7:30am-5pm
Contact: Jim Walker, Aerial Photography Manager
E-mail: walkerj@wsdot.wa.gov
Highlights: Over 500,000 negatives.
Dating from 1936-present (bits and pieces to 1950's): all highways were photographed regularly beginning in 1966; all highways and all counties are presently photographed.
Covers most of the Pacific Northwest: most of all 39 counties in Washington; most of Oregon, and up into Canada.
Scales range from 1:12,000-1:40,000.

COASTLINE CHARTS

National Geodetic Survey
Website: http://www.ngs.noaa.gov
Address: NGS Information Services
National Ocean Service
NOAA 1315 East-West Highway
Silver Spring MD 20910-3282
Phone: 301-713-3242
Hours: M-F, 7am-4:30pm (EST)
Fax: 301-713-4172
E-mail: info_center@ngs.noaa.gov
Highlights: Scales range from 1:5,000 to 1:40,000.
Earliest survey done in 1834.

DIGITAL ELEVATION MODELS AND ORTHOPHOTOS

United States Geological Survey: Earth Science Information Centers
Website: http://mapping.usgs.gov/esic/esic_index.html
Phone: 1-888-ASK-USGS (275-8747)
Highlights: Information and ordering for geologic maps and DEMs.

University of Washington: Earth and Space Sciences
Website: http://duff.ess.washington.edu/data/index.html
Highlights: Links to Digital Raster Graphics (7.5' topo maps); Digital Ortho Quads; 10-meter DEMs;1:24K (7.5-minute) quads; also 100K and 250K quads.

University of Washington Libraries: Map Collection and Cartographic Information Services
Website: http://www.lib.washington.edu/maps
Address: University of Washington Libraries
Box 352900
Seattle WA 98195-2900
Phone: 206-543-9392
Fax: 206-685-8049

Highlights: Information and ordering for geologic maps and DEMs.

Washington State Department of Natural Resources: Division of Geology and Earth Resources Geoscience Libraries in Washington
Website: http://www.wa.gov/dnr/htdocs/ger/geolibs.htm
Address: DNR Geoscience Libraries
PO Box 47007
1111 Washington Street SE, Room 173
Olympia WA 98504-7007
Phone: 360-902-1472
Fax: 360-902-1785
Highlights: Information and ordering for geologic maps and DEMs.

GEOLOGIC MAPPING

Washington State Department of Natural Resources: Division of Geology and Earth Resources Index to Geologic and Geophysical Mapping of Washington
Website: http://www.dnr.wa.gov/geology/
Highlights: Online index to geologic and geophysical mapping of Washington.

GOVERNMENT LAND OFFICE RECORDS (AKA: ANNUAL REPORTS OF THE CHIEF OF ENGINEERS)

Bureau of Land Management: General Land Office Records
Website: http://www.glorecords.blm.gov
Address: Division of Cadastral Survey & GLO Records
7450 Boston Boulevard
Springfield VA 22153-3121
Phone: 703-440-1600
Fax: 703-440-1609
E-mail: records@es.blm.gov
Hours: M-F, 8am-4:30pm
Highlights: Holds plat records for many states, including Washington State.

United States National Archives and Records Administration: Pacific Alaska Region (Seattle)
Website: http://www.archives.gov/facilities/wa/seattle.html
Address: 6125 Sand Point Way NE
Seattle WA 98115-7999
Phone: 206-526-6501
Fax: 206-526-6575
E-mail: seattle.archives@nara.gov
Hours: M-F, 7:45am-4:15pm
Highlights: Archival and record center holdings from Federal agencies and courts in Idaho, Oregon, and Washington State.
Microfilm holdings.

University of Washington Libraries: Microforms and Newspaper Collections
Website: http://www.lib.washington.edu/mcnews

Address: UW Suzzallo Library
Microform and Newspaper Collections, Room 150
Box 352900
Seattle WA 98195-2900
Phone: 206-543-4164
E-mail: mcnews@u.washington.edu
Hours: M-Th, 8am-10pm; F, 8-6; Sat, 9am-5pm; Su, Noon-10pm

Washington State Department of Natural Resources: Division of Geology and Earth Resources Library Services
Website: http://www.wa.gov/dnr/htdocs/ger/library.htm
Address: DNR Library Services
1111 Washington Street SE, Room 173
PO Box 47007
Olympia WA 98504-7007
Phone: 360-902-1472
Fax: 360-902-1785
E-mail: connie.manson@wadnr.gov
Hours: M-F, 8am-4:30pm
Highlights: Has microfiche copies of plats.

Washington State Historical Society: Museums and Resource Centers Research Center
Website: http://www.wshs.org/text/res_wshrc.htm
Address: WSHS Research Center
315 Stadium Way
Tacoma WA 98403
Phone: 253-798-5914
Fax: 253-272-9518
E-mail: researchcenter@wshs.wa.gov
Hours: Tu-Th, 12:30pm-4:30pm
Highlights: Owns paper copies of plat records.

LiDAR DATA

Central and Eastern Washington Lidar Consortium (Spring 2003)
Website: http://www.cwu.edu/~csi
Address: Center for Spatial Information
400 East Eighth Avenue
Central Washington University
Ellensburg Washington 98926
Phone: 509-963-1625
Highlights: LiDAR clearinghouse for central and eastern Washington.

National Oceanic and Atmospheric Administration Coastal Services Center
Website: http://www.csc.noaa.gov/crs/tcm/index.html

Address: NOAA Coastal Services Center
2234 South Hobson Avenue
Charleston SC 29405-2413
Phone: 843-740-1200
Fax: 843-740-1224
Highlights: Can access and order CD-ROM of LIDAR data on internet.
First mission in October of 1997, second in April of 1998.
Covers coast from Point Grenville, Washington into California.

PUBLISHED DATA

American Geological Institute: GeoRef
Website: http://www.georef.org
Highlights: Online database with bibliography.
Indexes references and selected abstracts to the world's literature in geology. Areas covered include North America since 1785, and other areas since 1933.
Available through the library homepages at most academic institutions, including the University of Washington, all Washington State Universities, and Whitman College.
Accessible only from campus, or with password.
There is also a print version of GeoRef: *Bibliography and Index Of Geology.* (See http://www.georef.org/access.html#bib for details and ordering information.)

Washington State Department of Natural Resources: Division of Geology and Earth Resources
Digital Bibliography of the Geology and Mineral Resources of Washington
Website: http://www.wa.gov/dnr/htdocs/ger/washbib.htm
Address: DNR Division of Geology and Earth Resources
PO Box 47007
Olympia WA 98504-7007
Phone: 360-902-1450
Fax: 360-902-1785
E-mail: geology@wadnr.gov
Highlights: Bibliographic information, articles, and books written on geology and mineralogy resources for each county in Washington.

Washington State Department of Natural Resources: Division of Geology and Earth Resources
Geosciences Libraries in Washington
Website: http://www.wa.gov/dnr/htdocs/ger/geolibs.htm
Highlights: Detailed list of libraries throughout Washington: includes contact information and summary of collections.

SOILS MAPS

United States Department of Agriculture: Natural Resources Conservation Service
Soil Surveys: Washington
Website: http://soils.usda.gov/soil_survey/pub_sur/wa.htm
Address: Washington State Office
USDA-Natural Resources Conservation Service

West 316 Boone Avenue, Suite 450
Spokane WA 99201-2348
Phone: 509-323-2900
Fax: 509-323-2909
Contact: Neil Peterson, State Soil Scientist
Phone: 509-323-2981
VoiceCom: 9035-2981
Fax: 509-323-2979
E-mail: neil.peterson@wa.usda.gov
Highlights: Soil surveys from most of Washington State.

United States Department of Agriculture: Natural Resources Conservation Service Soil Survey Status Maps: Washington
Website: http://www.wa.nrcs.usda.gov/technical/soils/index.html
Address: Natural Resources Conservation Service
West 316 Boone Avenue, Suite 450
Spokane WA 99201-2348
Contact: Raymond "Gus" Hughbanks, State Conservationist
Phone: 509-323-2900
Fax: 509-323-2909
Highlights: Description of soil types and maps of soils.

TOPOGRAPHIC MAPS

United States Geological Survey: National Geologic Map Database
Website: http://ngmdb.usgs.gov
Highlights: Searchable database.
Detailed bibliography for geologic maps and data.

United States Geological Survey: Online Map Lists
Website: http://mac.usgs.gov/mac/maplists/selectstatelist.html
Address: USGS Customer Services
EROS Data Center
47914 - 252nd Street
Sioux Falls SD 57198-0001
Phone: 800-252-4547
Phone: 605-594-6151
TDD: 605-594-6933
Fax: 605-594-6589
E-mail: custserv@usgs.gov
Hours: M-F, 8am-4pm (CT)
Highlights: Customizable map lists.
Scales range from 1:10,000-1:2,000,000.
Online map lists: where and how to order.