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Wetlands Regulatory Assistance Program (WRAP)

Synthesizing the Scientific Foundation for Ordinary High Water Mark Delineation in Fluvial Systems

Ellen Wohl, Matthew K. Mersel, Aaron O. Allen, Ken M. Fritz, Steven L. Kichefski, Robert W. Lichvar, Tracie-Lynn Nadeau, Brian J. Topping, Patrick H. Trier, and Forrest B. Vanderbilt

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Abstract

For more than 100 years, the ordinary high water mark (OHWM) has been used to define water boundaries in a number of contexts in the United States. This Special Report summarizes the scientific literature pertaining to the indicators used to identify the OHWM in fluvial systems, building on more than a decade of research and publications related to the OHWM in the ongoing process to implement the Clean Water Act and the Rivers and Harbors Act of 1899. This report does not change or redefine the indicators used to identify the OHWM, nor is it a manual for how to delineate the OHWM.

This report first reviews established concepts in river science that relate to the OHWM then reviews various sources of information that can be used to delineate the OHWM, discusses geographic variations in OHWM indicators among river segments, reviews human activities that can affect the OHWM, and finally presents examples of the OHWM in diverse channel types and regions.

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Preface

This study was conducted for the U.S. Army Corps of Engineers (USACE) Wetlands Regulatory Assistance Program (WRAP). The WRAP program manager was Sally Stroupe, CEERD-EM-W.

The work was performed by Ellen Wohl, Colorado State University; Matthew Mersel and Robert Lichvar (LiDAR and Wetlands Branch, David Finnegan, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL); Aaron Allen, Steven Kichefski, Patrick Trier, and Forrest Vanderbilt, USACE; and Ken Fritz, Tracie-Lynn Nadeau, and Brian Topping, U.S. Environmental Protection Agency. At the time of publication, Timothy Pangburn was Director of the Remote Sensing and Geographic Information Systems Center of Expertise (RS/GIS CX), ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

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Acronyms and Abbreviations

CV	Coefficient of Variation
CWA	Clean Water Act
CX	Center of Expertise
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System
HWM	High Water Mark
LiDAR	Light Detection and Ranging
NHD	National Hydrography Dataset
NHRAIC	Natural Hazards Research and Applications Information Center
OHWM	Ordinary High Water Mark
RHA	Rivers and Harbors Act of 1899
RS	Remote Sensing
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WRAP	Wetlands Regulatory Assistance Program

Executive Summary

For more than 100 years, the ordinary high water mark (OHWM) has been used to define water boundaries in a number of contexts in the United States. The OHWM is identified using indicators listed in Federal Regulations and is further clarified in the U.S. Army Corps of Engineers (USACE or Corps) Regulatory Guidance Letter 2005-05 (USACE 2005).

This technical report summarizes the scientific literature pertaining to the indicators used to identify the OHWM in fluvial systems. This report does not change or redefine the indicators used to identify the OHWM nor is it a manual for how to delineate the OHWM. This report builds on more than a decade of research and publications related to the OHWM in the ongoing process to implement the Clean Water Act (CWA) and the Rivers and Harbors Act of 1899 (RHA).

This report first reviews established concepts in river science that relate to the OHWM, including hydrographs; flow energy; channel stability and channel change; the active channel; bankfull, dominant, and effective discharge; environmental flows; and channel and stream heads. The report then reviews various sources of information that can be used to delineate the OHWM, discusses geographic variations in OHWM indicators among river segments, reviews human activities that can affect the OHWM, and finally presents examples of the OHWM in diverse channel types and regions. This report covers only aspects of the OHWM related to flowing waters and does not address standing waters such as lakes, wetlands, or coastal areas.

Three salient points emerge in the course of this report. The first is the need for regionally focused guidelines that recognize distinctive hydroclimatic and geomorphic influences within individual regions. The second is that the OHWM is not everlasting because of natural cycles and human-induced alterations to rivers. Naturally induced variations in river flow and channel geometry tend to be greatest in drier climates, but all rivers are continually adjusting to variations in water and sediment input, base level, and the erosional resistance of the channel boundaries. Human-induced variations are less easily generalized: the type and history of changes in land cover, flow regulation, channel geometry, and riparian vegetation tend to be very specific to individual river segments or river drainage basins. The third salient point is that the OHWM may be most effectively and

consistently delineated by constraining an elevation range defined by geomorphic and vegetative indicators that typically occur above, at, and below ordinary high water.

1 Introduction

1.1 Background

The ordinary high water mark (OHWM) has been used to delineate the jurisdictional limits of aquatic features in the United States since at least the 1899 Rivers and Harbors Act. The current Federal regulatory definition of the OHWM (33 CFR 328.3(e))* states, "The term *ordinary high water mark* means that line on the shore established by the fluctuations of water and indicated by physical characteristics such as [a] clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas." This definition suggests a physical mark shaped by relatively frequent flow. However, although the OHWM is defined in Federal Regulations, the OHWM has not been a major topic of study by hydrologists; and the term has not been thoroughly studied or considered in the scientific literature. Nonetheless, the intent of the OHWM seems straightforward: to delineate that portion of a river, lake, or other non-wetland water body that contains water at a reasonable frequency, including during relatively frequent floods rather than during unusual floods.

However, as noted by Field (2004), the Federal OHWM definition does not refer to the frequency with which the fluctuations of water occur. A common description of the OHWM equates it to the mark left by average peak flow over multiple years. The recurrence interval—the number that constitutes "multiple" in this description—is shorter in regions such as the humid-temperate eastern United States that typically have lower interannual hydrologic variability than drier regions such as the arid or semiarid western United States. However, the OHWM is not explicitly defined by or associated with a specific flow recurrence interval nationally.

In wetter parts of the country, a flow with approximately a 1- to 2-year recurrence interval commonly creates the OHWM. However, in arid regions with extremely variable flows, for example, the OHWM might be associated with a flow that recurs at time intervals on the order of every 5 to 10

* U.S. Congress. 1986. *Definition of "Waters of the United States."* Codified at 33 CFR 328.3 (et seq.). Washington, DC: U.S. Government Printing Office.

years and creates persistent channel morphology and high water marks associated with this flow magnitude (Lichvar and McColley 2008). Regional considerations are particularly important for delineating the OHWM in many rivers with such highly variable flow regimes, especially those that are dry for much of the time. Because there are such diverse geographic regions across the United States, there may be circumstances in which additional clarity as to what constitutes the frequency and magnitude of "ordinary high water" in a particular type of geographic region would be useful.

Moreover, some of the indicators found in the OHWM definition above could also be left by an extraordinary or long-recurrence-interval flood (Mersel and Lichvar 2014) that is larger than ordinary high water. This highlights the importance of understanding the scientific context of these indicators and the recent hydrologic history of a given site when identifying the OHWM.

General principles and example indicators have guided OHWM identification for more than 100 years; however, there is no single field guide for delineating the OHWM that accounts for all of the climatic and geographic variation across the country. Lichvar and Wakeley (2004), Lichvar and McColley (2008), and Mersel and Lichvar (2014) provide comprehensive and detailed reviews of multiple techniques for delineating the OHWM that are applicable to rivers in the arid western and western mountainous United States. Many of these techniques are applicable to any type of river, but other information can also be used. Because the existing technical reports are regional in scope and only cover a small portion of the United States, providing additional clarity for the full range of diversity in rivers present within the United States will be useful.

1.2 Approach

To make this information more easily accessible to regulatory practitioners, scientists, lawyers, policymakers, and others interested in delineating the OHWM, this report does the following:

- Reviews the interrelated concepts of the OHWM and the active channel, as these are used in scientific and regulatory contexts
- Reviews the related scientific concepts of bankfull, dominant, and effective discharge and channel change and stability
- Reviews the indicators of the OHWM and active-channel boundaries
- Reviews the literature on the upstream-most extent of channels

- Explains how the active channel varies among specific sites in relation to hydrology, climate, position within a drainage network, channel substrate, and human-induced alteration of the channel
- Provides examples of delineating the OHWM and the active channel in field settings that reflect the diversity of rivers present within the United States
- Discusses the relation of the OHWM and the active channel to nearby portions of the river corridor, including the floodplain, riparian zone, hyporheic zone, channel migration zone, and secondary channels

1.3 Definitions

River is used in this report to refer to any channel formed by water flowing at the surface and concentrated within a channel, as opposed to diffuse sheet flow or slope wash (Evrard et al. 2007; Antoine et al. 2012; Bierman and Montgomery 2014). This usage of *river* subsumes other commonly used terms, including *creek*, *brook*, *stream*, *gully*, *wash*, and *tributary*. These terms typically refer to smaller channels, but there are no consistently used criteria in terms of channel dimensions or flow rate that distinguish a stream from a river, for example.

Active channel is another phrase used widely but inconsistently in the scientific literature (Table 1). Some authors use the phrase to refer to the unvegetated portion of the channel (e.g., Johnson 1994) whereas other authors use *active channel* to distinguish the portion of a channel below which the banks slope steeply (e.g., Osterkamp 2008). The second usage can be different from the first along rivers in which, following a flood, vegetation encroaches on the channel margins more rapidly than banks eroded to a vertical configuration return to a lower slope angle.

Table 1. Definitions in scientific literature of the active channel.

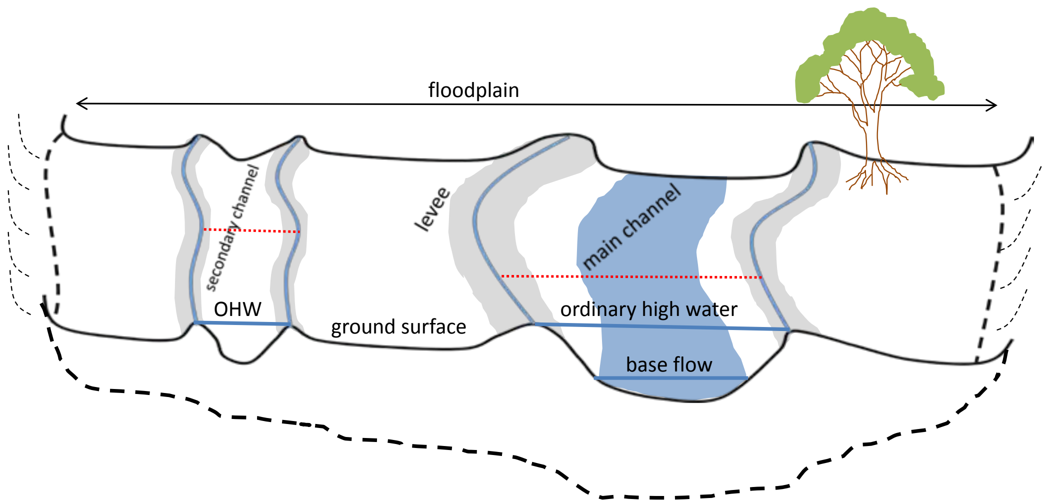
Definition of active channel	Reference
"The active channel is the lower part of the channel entrenchment in the floodplain that is actively involved in the transportation of water and sediment during the usual regime of a stream . . ."	Hedman et al. (1974)
"[A] short term geomorphic feature . . . The upper limit is defined by a break in the relatively steep bank slope . . . normally coincides with the lower limit of permanent vegetation . . . beneath the reference level is that portion of the stream entrenchment in which the channel is actively, if not totally, sculptured by the normal process of water and sediment discharge."	Osterkamp and Hedman (1977, 1982)
"At most perennial and intermittent streams the active-channel level is exposed between 75 and 94 percent of the time. The active-channel level of many ephemeral streams may be exposed more than 99 percent of the time. The state corresponding to mean discharge of most perennial streams approximates that of the active-channel . . . but is lower than the active-channel level of the highly ephemeral channels . . ."	Hedman and Osterkamp (1982)
"[A]ctive channel (unvegetated sand and water)"	Johnson (1994)
"[T]he active channel, described by Osterkamp and Hedman [1982] as a morphological bench inset within the bank-full channel, and is assumed to form during high-frequency, low magnitude flows."	Kolberg and Howard (1995)
"[T]he active channel reference level, which approximates the width at the mean annual discharge . . ."	Friedman et al. (1998)
"[A]n active channel (here used to refer to the open, unvegetated sand-and-gravel channel). . ."	Kondolf et al. (2001)
"Active channel of an alluvial stream is a short-term geomorphic feature subject to change by prevailing discharges; its upper limit is defined by a break in the relatively steep bank slope of the active channel to a more gently sloping surface beyond the channel edge. The break in slope normally coincides with lower limit of perennial vegetation so that the two features, individually or in combination, define the active-channel reference level."	Osterkamp (2008)
"Active channel" refers here to the unvegetated gravel bars and low-flow channels.	Lallias-Tacon et al. (2014)
"The active channel width β corresponds to the non-vegetated river width and thus includes secondary channels and sand bars frequently altered during flood events."	Latapie et al. (2014)
"The active channel is defined as the area without shrub vegetation, thus including unvegetated bars and active and inactive channels, whereas the fluvial islands class include pioneer, young and stable islands according to Gurnell and Petts (2002) classification."	Moretto et al. (2014)
"The active channel area and width were calculated from the photos and correspond to the area of water and un-vegetated sediment bars."	Picco et al. (2014)
"Active channel areas and widths (A_{GB}, W_{GB}) were defined as the total channel area and width, excluding all midchannel islands and clusters of vegetation ($A_T – A_V = A_{GB}$; where the subscript *GB* refers to gravel and bedrock)."	Toone et al. (2014)
". . . the active channel, considered the surface comprising water surface and sediment bars free of vegetation, and the riparian corridor, considered as the surface of the pioneer and stable vegetation, plantations and riparian forest (Rinaldi 2003; Surian and Rinaldi 2003)."	Besne and Ibisate (2015)
"The active channel (defined by the low-flow channel and unvegetated gravel bars) . . ."	Arnaud et al. (2015)
". . . the active channel (AC) (Slater 2007), the latter corresponding to the area occupied by water channels and bare sediments . . ."	Belletti et al. (2015)

In this report, the *active channel* refers to a portion of the valley bottom that can be distinguished based on three primary criteria. The active channel commonly meets one of these three criteria in any river system, but all three criteria rarely apply to any single system.

The active channel can be designated as

- any portion of a valley bottom within channels defined by erosional and depositional features created by river processes as opposed to upland processes such as sheet flow or debris flow (Figure 1; this criterion is particularly useful for rivers with multiple channels, such as braided rivers);
- the upper elevation limit at which water is contained within a channel as opposed to spreading across the floodplain or valley bottom (this may not be an appropriate criterion for deeply incised channels); and
- portions of a channel generally without trunks of mature woody vegetation (the active channel can include newly germinated woody seedlings or various wetland ecological response species, including rooted aquatic macrophytes such as sedges or rushes. In very small channels, the roots of mature woody vegetation can cross the channel), where coarse sediment is mobilized and transported during annual flooding.

Figure 1. Three-dimensional block diagram illustrating the width and elevation of the active-channel boundaries as *dotted red lines*. In this example, the main channel has a perennial base flow, whereas the secondary channel is ephemeral. In this example, active-channel boundaries of the main and secondary channel are at the top of the natural levee (here indicated by *gray shading* and vertically exaggerated to increase visibility), above which flow is not contained within a channel and spreads across the floodplain.



In perennial rivers that include longitudinally continuous surface flow throughout the year, the active channel may coincide with the mean annual peak discharge; but the active channel can be associated with flows that occur over a range of return intervals in diverse rivers. The OHWM is coincident with the active channel on rivers with limited variability in discharge through time. The OHWM can be lower than the active-channel boundaries in rivers with large variability in discharge through time and in channels where evidence of extraordinary floods persists longer than the return interval of the extraordinary flood. Ordinary high water flows are typically confined to a channel; but in some rivers, the high flow that recurs every 1 to 2 years can extend above and beyond the channel and across the adjacent valley bottom. If the high flow overtops the channel banks more years than not, then the OHWM may lie beyond the channel banks if sufficient physical evidence is present. In this scenario, this overtopping high flow is the ordinary high water flow and is used to define the OHWM if the flow leaves a mark.

The *geomorphic floodplain* is a relatively flat sedimentary surface adjacent to the active channel and separated from the channel by banks. The floodplain is built by river processes, composed of sediment transported by the present flow regime, and inundated frequently (Nanson and Croke 1992). Although there is no absolute definition for frequency of inundation, active floodplains are commonly inundated at least once every 10–20 years, and many floodplains are inundated every 1–2 years.

1.4 Management context for using the OHWM

The OHWM is relevant in several regulatory and management contexts. The first involves the concept of navigation servitude, which defines national sovereignty over navigable waters of the United States. Under navigation servitude, the Federal Government under the commerce clause of the Constitution can require the removal, relocation, or other alteration of the structure or work authorized under Section 10 of the Rivers and Harbors Act without expense to the United States if it becomes an obstruction to navigation. In addition, under 33 USC Section 595(a), the Federal Government can take property "for the public use in connection with any improvement of rivers, harbors, canals, or waterways of the United States"; and "compensation to be paid for real property taken by the United States above the normal high water mark of navigable waters of the United States shall be the fair market value of such real property."[*]

A second context involves property boundaries. The OHWM serves as the property boundary for lands along rivers in some cases[†] whereas the low water mark is used in other cases.[‡] Use of a low water mark assumes that the channel never goes dry. Other property ownership rules across the nation also apply to river ownership (33 CFR 329.11)[§], which varies by state law.

A third context in which the OHWM is used involves regulatory jurisdiction. The OHWM is used by the U.S. Army Corps of Engineers (USACE or Corps) to delineate the lateral limits of non-tidal navigable waters of the United States under the Rivers and Harbors Act of 1899. In addition, the Corps, the U.S. Environmental Protection Agency (EPA), and many states delineate wetlands and other waters of the United States under Corps and EPA regulations implementing the Clean Water Act (CWA). In non-tidal, non-wetland waters of the United States lacking adjacent wetlands, CWA jurisdiction extends to the OHWM.

* U.S. v. Chicago, M., ST. P. & P. R. CO. 1941.

† Lopez v. Smith (boundary dispute). 1959. 109 SO 2D 176-180 (FLA DCA).

‡ Vermont v. New Hampshire (Boundary Dispute Involving River Between States). 1933. 289 US 593, 53 SUP CT 708–718.

§ U.S. Congress. 1986. *Geographic and Jurisdictional Limits of Rivers and Lakes.* Codified at 33 CFR 329.11 (et seq.). Washington, DC: U.S. Government Printing Office.

2 The OHWM and the Active Channel in the Context of River Science

This section reviews concepts from river science—hydrology, geomorphology, and river ecology—that are relevant to understanding the OHWM. Rivers are dynamic environments that change through time and across space. The inputs of water and sediment entering a river segment from upstream portions of the river network or adjacent uplands are the primary variables that shape channel and valley-bottom morphology. Water and sediment inputs change continuously in response to weather, climate, and land use. This chapter reviews scientific understanding of how these continual changes in the driver variables influence channel morphology and OHWM.

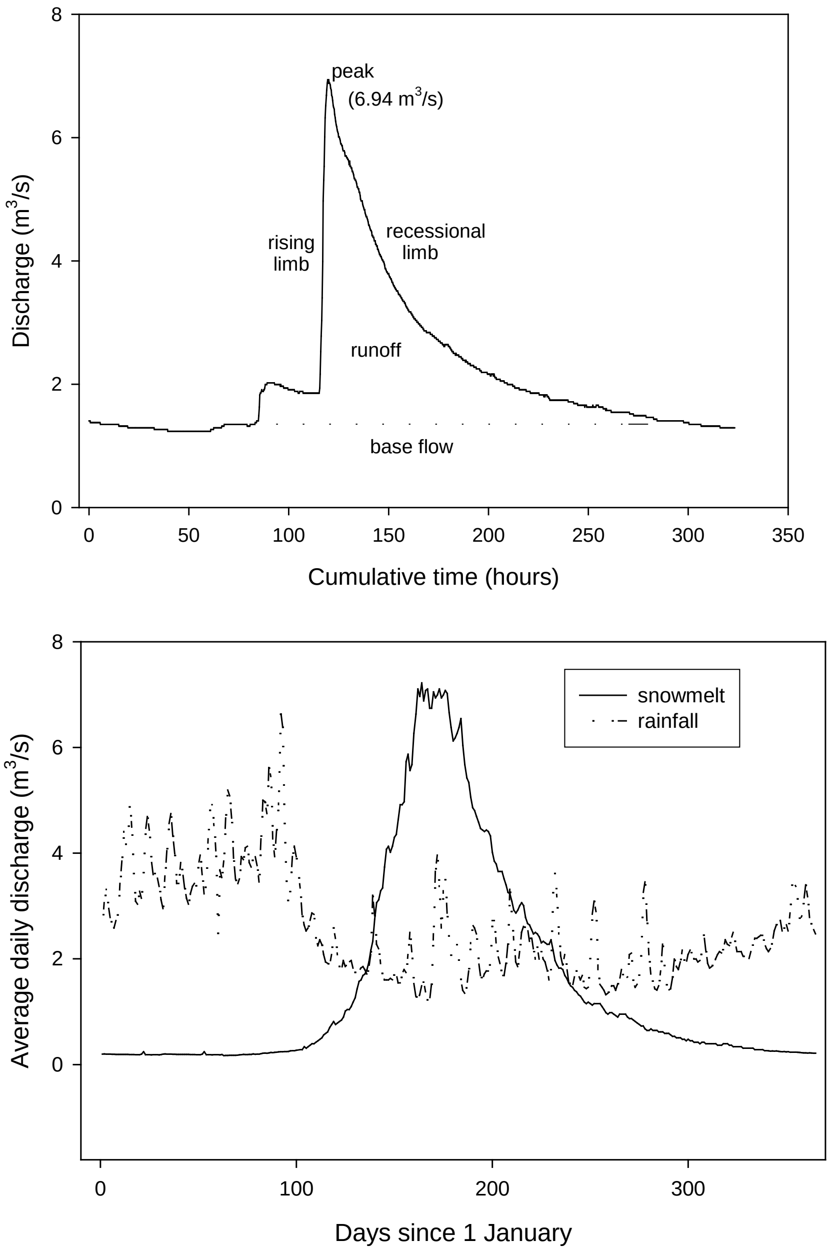
2.1 Objectives

This report aims to summarize the scientific literature pertaining to the OHWM and its indicators in fluvial systems across the United States. The information presented here can serve as the scientific foundation for future efforts to develop OHWM delineation manuals.

2.2 Hydrographs, flow energy, and sediment transport

The OHWM was used early in United States history to define property boundaries and navigation, presumably in recognition that river flow fluctuates during the course of a year, reaching seasonal high and low levels that have some level of consistency. Hydrologists describe river flow by using a hydrograph, or plot of discharge versus time, over time intervals that vary from a single storm to a year or several years (Figure 2). Base flow is the magnitude of discharge that remains relatively constant over time periods of days or longer in a river and is supplied primarily via groundwater inputs to a river. Runoff, also known as direct flow, is the portion of flow that enters a river via surface and shallow subsurface flow paths after precipitation or snowmelt within a drainage basin (Figure 2).

Figure 2. (*A*) Flood hydrograph illustrating base flow and storm runoff. (*B*) Annual hydrographs for different types of streamflow regimes (after Wohl 2014c, Fig. 3.18).



Discharge is a volume of river flow per unit time, typically expressed as cubic meters per second or cubic feet per second. Discharge is the product of flow width multiplied by flow depth and flow velocity. Because depth can be easily measured by using a scale on the side of a channel or a pressure transducer (Figures 3 and 4), discharge is commonly measured by using a rating curve that equates flow stage, or water-surface elevation within the channel, to discharge. The rating curve is developed by repeatedly measuring all three parameters (width, depth, and velocity) within a channel during different volumes of flow and then assuming that the stage–discharge relationship remains constant through time between successive measurements that are used to recalibrate the curve (McMillan et al. 2010; Bierman and Montgomery 2014). The assumption that erosion or deposition within a channel cross section does not change the stage–discharge relationship is most likely to be accurate at sites with erosionally resistant channel boundaries formed by bedrock, cohesive sediment such as silt and clay, or infrastructure such as bridges with hardened river banks or bed. Partly for this reason and partly for ease of access, gaging sites are commonly located at bridges.

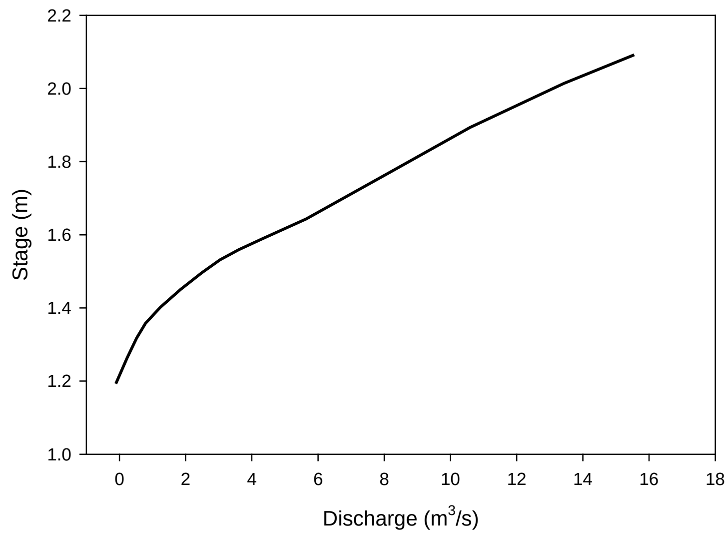
Perennial rivers are those that in a typical year flow at all times and along the entire length of the channel under consideration. Perennial flow occurs because the riparian water table is located above the stream bed for most of the year and groundwater is the primary source of water for river flow. Runoff from snowmelt and rainfall is a supplemental source of water for river flow.

Figure 3. Example staff gages.

A staff gage at the base of a bridge across the South Fork Poudre River in Colorado. Channel is approximately 10 m wide, and flow is from right to left.

A staff gage on the Colorado River at Lees Ferry, Arizona. Flow is from left to right and the staff gage is on the far side of the channel against a bedrock outcrop.

Figure 4. Sample stage–discharge rating curve, in this case for North St. Vrain Creek, Colorado (drainage area 90 km^2). This site has a strong annual snowmelt peak flow. The break point, which represents the stage at which the river spreads out of its banks, is between 1.4 and 1.6 m at this site.



Many rivers, however, do not have continuous surface flow at all times. These rivers are designated as either ephemeral or intermittent. Ephemeral rivers are those that flow only during and soon after precipitation inputs; these rivers have no groundwater inputs or base flow (Figures 5–7). The Corps Nationwide Permits define ephemeral rivers as those that have "flowing water only during, and for a short duration after, precipitation events in a typical year. Ephemeral stream beds are located above the water table year-round" (USACE 2012). Intermittent rivers flow continuously only at certain times of the year when the water table intersects the surface along the river course, such as when the river receives water from a spring or from a surface source such as melting snow (Osterkamp 2008). During periods of low flow, dry segments alternating with flowing segments can be present, a condition referred to as discontinuous flow. The USACE (2012) Nationwide Permits define intermittent rivers as having "flowing water during certain times of the year, when groundwater provides water for stream flow. During dry periods, intermittent streams may not have flowing water. Runoff from rainfall is a supplemental source of water for stream flow." This definition focuses on the temporal component of flow and is used in some scientific papers (e.g., Reynolds et al. 2015). Other usages of *intermittent* focus on the spatial component of flow and are used to describe a scenario in which a river can have surface flow for some limited distance downstream from a spring although that water can infiltrate into the streambed and leave a dry channel farther downstream (Bierman and

Montgomery 2014). An intermittent river can also have continuous surface flow resulting from runoff for a limited period of time following precipitation and then return to longitudinally discontinuous base flow over longer time periods (Figure 8), as reflected in the USACE definition above. Another term sometimes used is *temporary rivers*, which refers to rivers that cease to flow at some points in space and time along their course (Arthington et al. 2014).

Figure 5. Examples of ephemeral channels from diverse locations.

Upper Antelope Creek in central Arizona

Ephemeral drainage in Sacramento County, California

Ephemeral channel in El Dorado Valley, Nevada

Ephemeral channel in Hoosier National Forest, south-central Indiana

Figure 6. Deeply incised ephemeral channels on the Pawnee National Grassland in eastern Colorado. The channel at *left* is incised into soft bedrock (daypack for scale). At *right* is an abrupt headcut (~3.5 m tall) eroding upstream along an alluvial channel. Both of these channels drain an area of less than 1 km^2, and flows never reach the top of the banks.

Figure 7. Examples of ephemeral channels from various locations.

Flow in an ephemeral channel in Robinson Forest, eastern Kentucky

Headcut along an ephemeral channel in Shawnee National Forest, southern Illinois

Ephemeral channel in Edge of Appalachia Preserve, southern Ohio.

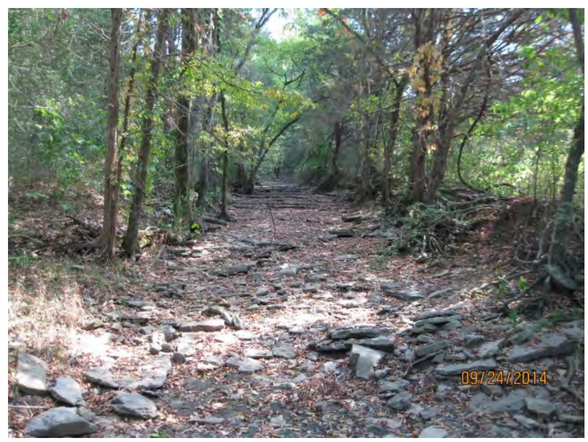
Figure 8. Examples of intermittent channels from diverse locations.

Bumblebee Creek in central Arizona

Intermittent channel in eastern Oregon. Trichoptera (caddisfly) cases highlighted by the *white oval* in the inset photo are from a species that requires at least intermittent flow to complete its life cycle.

Intermittent channel near Nolensville, TN

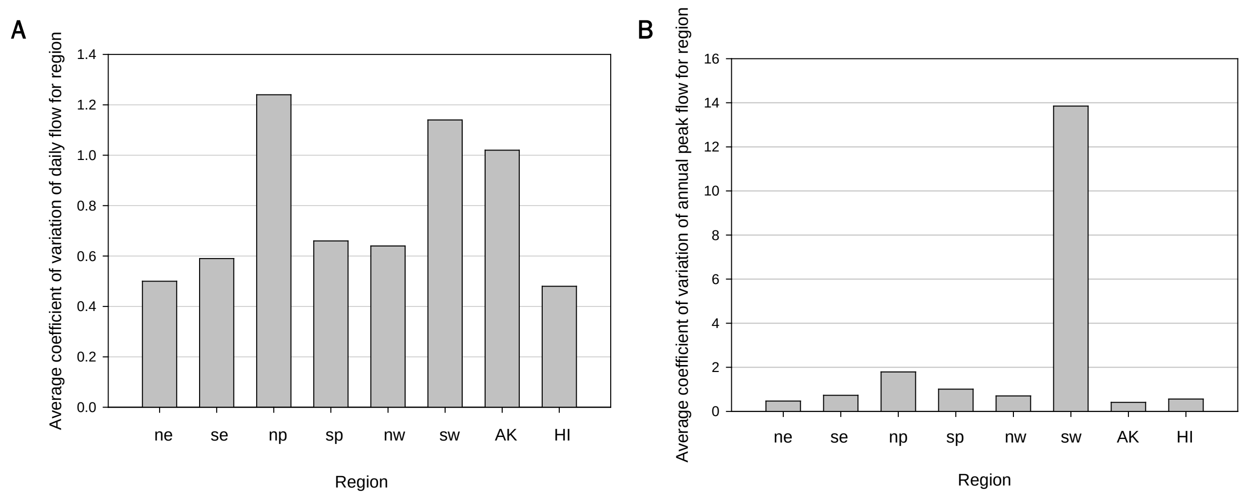
Intermittent channel near Nolensville, TN



Intermittent channel near Durham, Connecticut

Hydrologic variability, as used in this report, refers to fluctuations in river flow through time. Hydrologic variability can be described for varying time periods. Forms of hydrologic variability particularly relevant to the OHWM include intra-annual time periods, or variation in flow throughout a year, and interannual time periods, or variation in flow between years. As a general rule, intra- and interannual flow variability increase as average annual precipitation decreases. In other words, rivers in drier climates tend to have greater flow variability within an average year and between years than rivers in wetter climates (Figure 9). This reflects the consistent presence of base flow in wetter climates; base flow tends to decrease the difference in magnitude between seasonal or intra-annual low and high flows and between high flows of successive years. Drier climates also tend to have larger values of peak discharge per unit drainage area (i.e., $ft^3/s/mi^2$ or $m^3/s/km^2$) than drainages in wetter climates up to drainage areas of approximately 2600 km^2 because dryland regions typically have poor soil development and sparse vegetation, which promote surface runoff rather than infiltration (Graf 1988). For larger drainage areas, the larger amounts of rainfall in humid regions generate larger floods (Graf 1988).

Figure 9. Coefficient of variation in river flow averaged over multiple gaging stations within a region for (*A*) daily average flow and (*B*) annual peak flow. Regions are ne (northeast; wet), se (southeast; wet), np (northern prairies; dry), sp (southern prairies; dry), nw (northwest; moderate), sw (southwest; dry), AK (Alaska; moderate), and HI (Hawaii; wet). For additional information, see Table 2.



Within a particular type of climate, river segments with smaller drainage areas also tend to have greater intra- and interannual flow variability than river segments with larger drainage areas. Small drainage areas are more likely to be completely covered by the intense rainfall associated with a convective storm, which can generate higher magnitudes of peak flow per unit drainage area than can occur in river segments draining larger areas, which are less likely to be completely covered by intense rainfall during any single storm (Hirschboeck 1988). Drainage areas larger than approximately 70 km^2 will rarely be covered by a single thunderstorm (Graf 1988; O'Connor and Costa 2003, 2004).

Large intra-annual flow variability can generate multiple high water marks (HWMs), making it more difficult to distinguish the OHWM. Note that a HWM is simply the physical evidence of one or more flow events, which may or may not represent the "ordinary" HWM. Large interannual flow variability is likely to create more problems in distinguishing the OHWM from marks left by floods with longer recurrence intervals, however, both because the extraordinary-flood HWMs may persist and because the ability to distinguish the OHWM at a particular river segment may be limited by the presence of recently created extraordinary HWMs.

The distributions of flow through time and along a river have important implications for the channel's shape and the transport of sediment, nutrients, and contaminants within the channel. At the most basic level, water flowing down a channel is converting potential energy to kinetic energy. Some of this energy is used to overcome frictional resistance created by the channel boundaries and by differential movements of individual water molecules, and some of the energy is used to erode the channel boundaries and to transport sediment.

Sediment can be transported as solutes, known as dissolved load. Although this component of sediment transport can be substantial in some rivers, most of the dissolved material comes from subsurface sources, such as groundwater inputs, because groundwater has longer reaction times with the surrounding matrix. Particulate sediment can be carried in suspension within the water column or transported in contact with the bed. Suspended load includes wash load, which is the finest size fraction of the total sediment load (typically grains with intermediate diameters less than or equal to 0.062 mm), and consists of particles typically not found in large quantities on the bed surface. Suspended load also includes coarser grains that are found in large quantities on the bed surface and that require some minimum velocity to remain in suspension. These larger grains are part of the bed-material load, which includes all grains coarser than 0.062 mm in diameter. These grains move either in contact with the bed by rolling, sliding, or bouncing as bed load or move in suspension just above the bed surface with concentration declining upward from the bed (Wohl 2014c).

Flow energy can be expressed as the product of discharge and channel gradient; so as discharge increases within a channel, more energy is available to erode the channel boundaries and carry sediment. A very large flood has substantial energy but occurs only infrequently. A more moderate flood—perhaps of a size that occurs on average once a year—has less energy but occurs more frequently. The tradeoff between magnitude and frequency has been systematically examined by geomorphologists trying to understand what floods are most important in shaping a channel and carrying sediment. This has led to the interrelated concepts of channel stability and channel change as well as bankfull discharge, dominant discharge, and effective discharge.

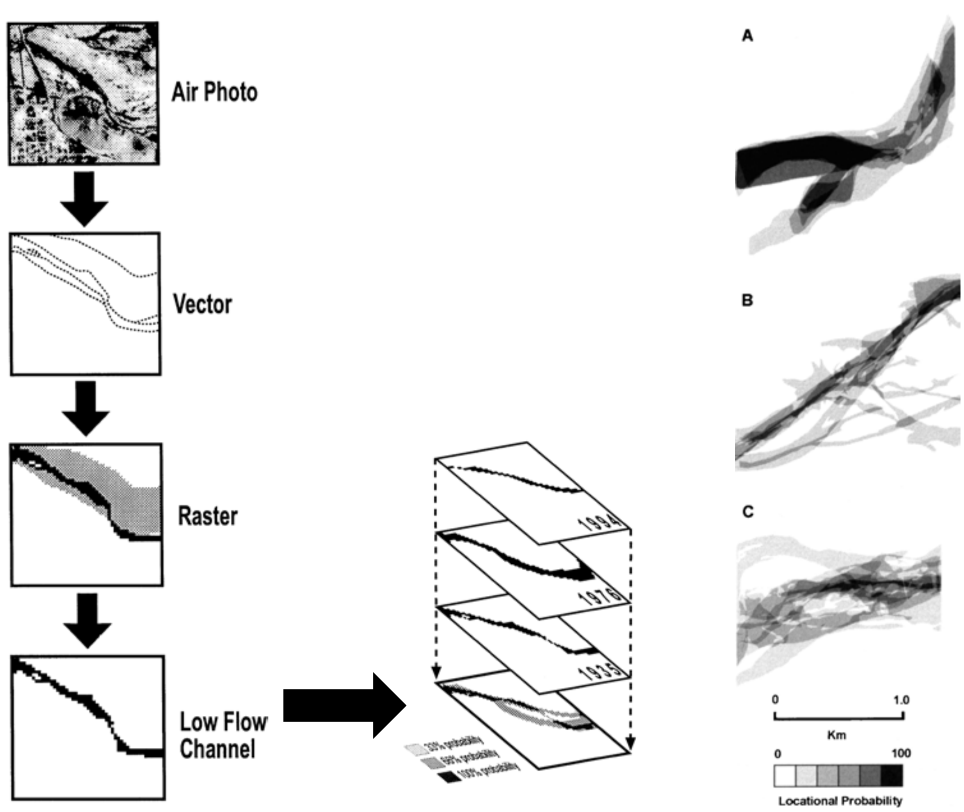
2.3 Channel stability and channel change

A stable channel can be defined as one with no net change in channel geometry over the time interval being considered. Defining the relevant time interval is crucial because natural channels continually change. A period of very low flow may allow silt to accumulate on the channel bed, for example, because transport capacity is reduced; or a flood may erode the channel bed and banks because flow energy exceeds sediment supply during the flood. In each case, the channel change that occurs over a period of months for the drought, or days for the flood, may be completely removed by subsequent flows; a period of higher base flow following the drought can remove the silt, or lower flows after the flood can deposit sediment along the bed and banks.

Definitions of channel stability date to at least Mackin (1948), which defined a graded river as a channel in which streambed slope is adjusted to prevailing water and sediment discharges, such that the channel neither aggrades nor degrades and the slope remains constant over the time interval of interest. Mackin and other geologists who have considered channel stability may be focused on time intervals of hundreds to thousands of years or longer. In a river management context, time intervals of years to decades are likely to be more relevant.

Separating the “noise” of short-term fluctuations from longer-term trends can be challenging at management-relevant time intervals if records of channel morphology are limited. A channel that abruptly shifts its location from one side of a valley bottom to the other during a flood can seem to be unstable, for example; yet a multi-decadal record of channel position can record repeated lateral movements, or avulsions, across the valley bottom for some types of rivers (Graf 2000) (Figure 10). In other words, channel avulsions are ordinary behavior for some types of channels, such as braided or anastomosing rivers, and do not necessarily indicate that the river has become unstable (Ashmore 2013; Nanson 2013; O'Connor et al. 2015). Another example comes from channels that widen substantially and change planform—typically to a braided channel—during a flood that lasts a few hours and then gradually narrow to a sinuous, forested channel over a period of decades. These are rivers that, over periods of a few decades, repeatedly alternate between distinctly different channel morphologies. Examples have been documented in the Mediterranean climate of southern California (Kondolf et al. 2001), the semiarid Great Plains (Friedman and Lee 2002), and high desert/semiarid grasslands in southern Arizona (Burkham 1972) and western Colorado (Jaquette et al. 2005).

Figure 10. Illustration of using aerial photographs to develop a locational probability map (*left* and *center*) for a channel that shifts location across a floodplain through time. On the *right*, examples of locational probability maps from the Salt River near Phoenix, Arizona, based on 1935–1996 data (from Graf 2000, Fig. 5 [*left* and *center*] and Fig. 9 [*right*]).



Geomorphologists have distinguished transient and persistent river forms based on the recurrence interval of the flow that creates a form versus the length of time that the river form is present. A transient river form (e.g., channel width-to-depth ratio, meander wavelength, and downstream spacing of pools and riffles) is one that has a shorter duration than the recurrence interval of the flow that created it. Conversely, a persistent river form has a longer duration than the recurrence interval of the flow that created it. Persistent forms are likely to be created by relatively frequent flows; and the concepts of bankfull, dominant, and effective discharge are used to describe these frequent, channel-forming flows.

2.4 Bankfull discharge

The concept of bankfull discharge, although widely used in river science and management, is problematic because of conflicting and inconsistent definitions. Bankfull discharge has been defined with reference to channel morphology (Figure 11; Table 2) and with reference to recurrence interval (Simon et al. 2004), but the two forms of the definition are not necessarily consistent. Bankfull discharge has also been delineated biologically, based on the presence of specific invertebrate species (Radecki-Pawlik and Skalski 2008).

The first formal definition of bankfull discharge comes from Wolman and Leopold (1957), who defined it as the flow depth just before flow begins to overtop the banks. This definition clearly relies on channel morphology and on being able to distinguish the top of the banks. Most papers that explicitly define bankfull discharge have a closely related description based on channel morphology (Figure 11; Table 2).

Numerous subsequent studies indicate that a flow that nearly overtops the banks recurs approximately every 1 to 2 years on many perennial rivers (Leopold et al. 1964; Castro and Jackson 2001). Because of this, bankfull discharge is sometimes defined based on recurrence interval rather than on flow depth with respect to channel geometry. This usage typically defines bankfull flow as occurring every 1 to 2 years (Simon et al. 2004; Osterkamp 2008).

dominate sediment transport at some sites, such as in drier climatic regions. Subsequent studies reinforced the finding that relatively frequent floods transport the greatest amount of suspended sediment over a period of multiple decades along many rivers (e.g., Simon et al. 2004), which has led to the idea that bankfull discharge is the most important flow magnitude for controlling channel geometry and sediment transport (Dunne and Leopold 1978).

Figure 11. Illustrations of bankfull, dominant, and effective discharge. (*A*) Morphological components of a channel cross section relevant to bankfull discharge: ToB is top of bank, BI is bank inflection, BSB is bank slope break, BoB is base of bank, AX is channel axis (thalweg) (from Navratil et al. 2006, Fig. 2). (*B*) Dominant discharge, if defined based on sediment transport (e.g., product of transport magnitude and frequency), is equivalent to effective discharge. At *left*, effective discharge as originally illustrated in Wolman and Miller (1960, Fig. 1). At *right*, illustration in Bunte et al. (2014, Fig. 1) based on bedload transport. Q_{bf} is bankfull discharge, Q_{eff} is effective discharge, Q_B is sediment transport rate, and F_Q is flow frequency.

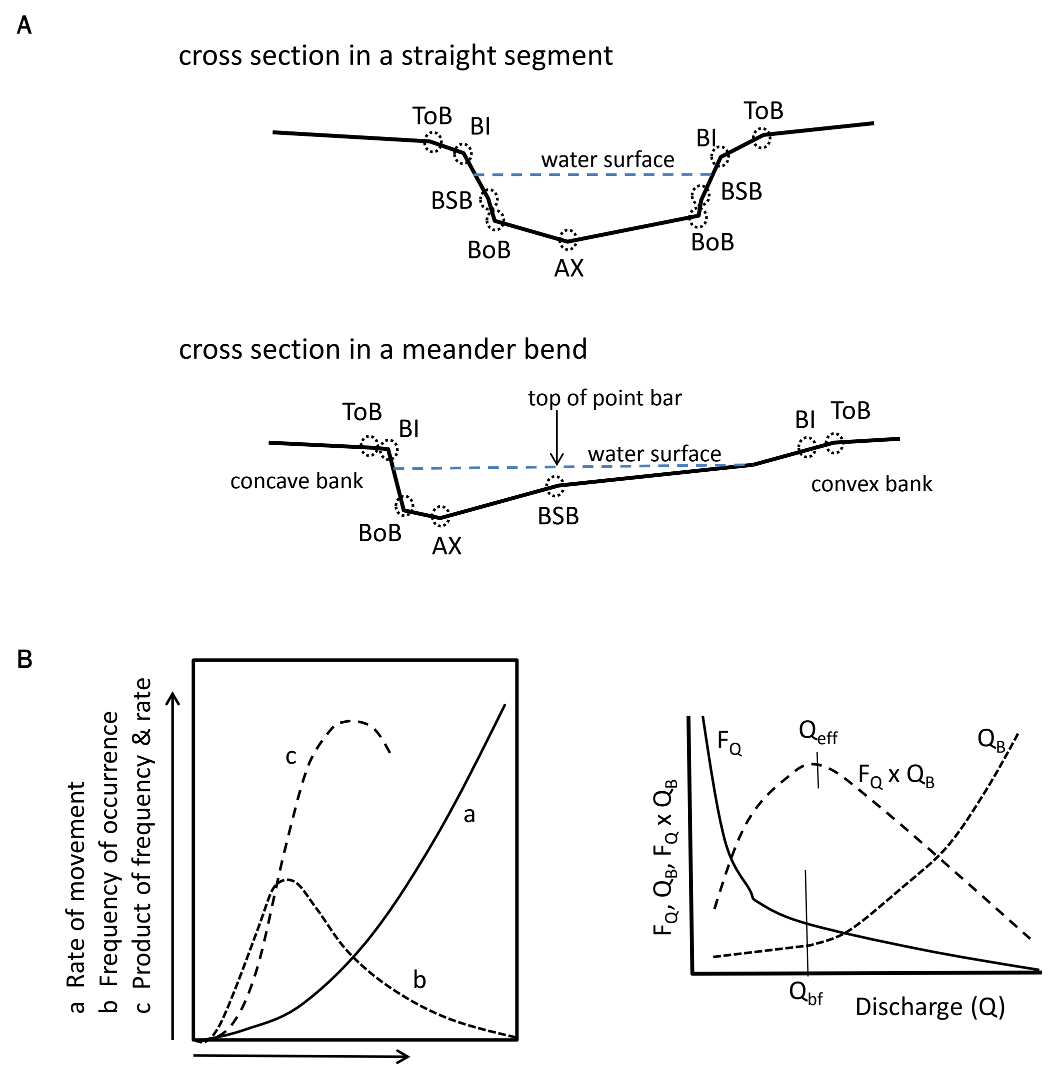


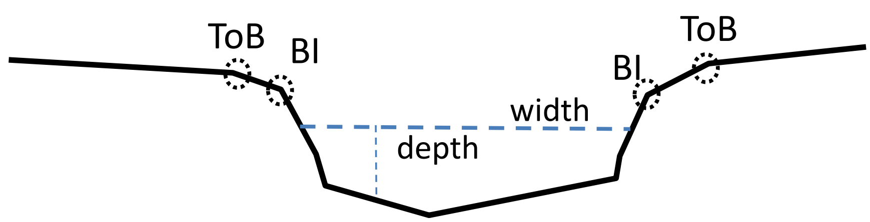
Table 2. Definitions of bankfull discharge in the scientific literature.

Definition of bankfull discharge	Reference
Bankfull discharge is the flow in a river channel at the level of transition from the active channel to the flood plain.	Wolman and Leopold (1957) Leopold et al. (1964)
“When a well-developed flood plain is present its surface can be considered as the level of the bankfull stage. . . . The following seem to occur at a consistent height above the water surface and are taken to represent bankfull level: a) Moss, and sometimes lichens, growing on shore boulders are often truncated at a particular level above low water . . . b) Sand mixed with river boulders often extends up to a particular level. The upper limit of sand deposited in shore boulders is usually coincident with bankfull flow. c) Vegetation tends to change progressively with elevation along the stream. The lower limit of herbs and forbs usually represents bankfull stage. d) Flood debris of old sticks, pine cones, and trash . . .”	Leopold and Skibitzke (1967)
“Eleven possible definitions of ‘bank-full’ have been used by various investigators. The active floodplain is the most meaningful bank-full level . . . The bank-full discharge at a river cross section is the flow which just fills the channel to the tops of the banks.”	Williams (1978a)
“The bankfull discharge was defined as the discharge which filled the channel to the level of the floodplain.”	Andrews (1980)
“The bankfull discharge, corresponding to the bankfull depth . . .”	Johnson and Heil (1996)
“Bankfull discharge is the flow sufficient to overtop the banks of a natural channel and begin to spread across the floodplain. It is the discharge of incipient flooding.”	Surian and Andrews (1999)
Following the definition of Williams (1978a), “. . . bankfull discharge value for a mountain stream should not be reported as a single number, but rather as a range of discharges within which one could expect the bankfull value to lie.”	Radecki-Pawlik (2002)
“. . . the bankfull discharge is the maximum discharge that can be contained within the channel without overtopping the banks (Leopold et al. 1964) and generally accepted to represent the flow that occurs, on average, every 1.5 years ($Q_{1.5}$).”	Simon et al. (2004)
“Bankfull discharge, a hydrologic term, is the flow rate (m^3s^{-1}) when the stage (height) of a stream is coincident with the uppermost level of the banks—the water level at channel capacity, or bankfull stage. Thus, the concept of bankfull discharge, which often approximates the mean annual flood for perennial streams, includes the flood plain as a unique, identifiable geomorphic surface, all higher surfaces of alluvial bottomlands being terraces, and acknowledgement that bankfull discharge occurs only when stream stage is at flood-plain level.”	Osterkamp (2008)
“The flow at the bankfull level is considered as the bankfull discharge (Q_b) . . .”	Roy and Sinha (2014)

Bankfull flow is also assumed to imply some level of sediment transport. Wolman and Miller (1960) examined stream gage records of flow and suspended sediment transport from across the United States. They found that relatively frequent floods—those that occurred on average every 1 to 2 years—transported the majority of suspended sediment through time at many gaging sites, although they did note that extraordinary floods could

Bankfull discharge is now one of the most widely referenced discharges in river management because it is commonly used as the design discharge in river restoration (Rosgen and Silvey 1996; Rosgen 2006). This is problematic for several reasons. First, bankfull discharge can be difficult to define based on channel geometry. Even though regional curves can help to estimate channel dimensions based on drainage area (e.g., Bieger et al. 2015), natural rivers can have inset channels, uneven bank heights on the two sides of the channel, or multiple convexities along the side slopes that reflect different flow magnitudes. For example, the channel can also be so deeply incised as a result of processes that do not result from surface flow within the channel (e.g., subsurface piping), that the top of the bank has little relevance to flow volume (Figure 5). As another example, channel engineering may have altered channel dimensions so that channel form no longer reflects flow volumes. Individual investigators have defined bankfull depth based on top of bank, bank inflection, ratio of channel width to mean depth, level of significant change in the relationship between wetted area and top channel width, and first maximum local bank slope (Williams 1978a) (Figure 12). Lack of consistency in defining bankfull flow based on channel geometry as a result of using different indicators means that discharge estimates can vary by as much as a factor of three at a given site (Radecki-Pawlik 2002; Navratil et al. 2006).

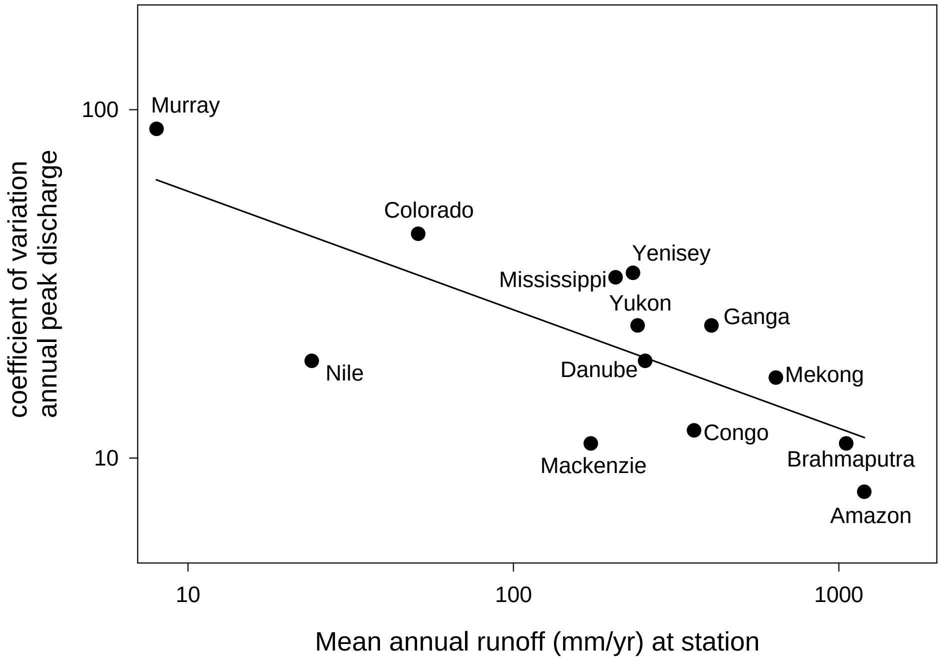
Figure 12. Illustration of different morphological indicators of bankfull: top of bank (ToB), bank inflection point (BI, also sometimes known as the first maximum local bank slope), and ratio of channel width to mean depth.



A second problem with using bankfull discharge as a design discharge in river restoration or as a management tool is that bankfull discharge defined in relation to channel geometry can have very different recurrence intervals among different sites (Williams 1978a; Petit and Pauquet 1997). As a general rule, rivers in drier climatic regions typically have greater annual and interannual variability in flow although flood magnitude in rivers with wetter climates can also vary substantially from year to year (Figure 13). Consequently, the flow that actually fills a channel to the top of the banks, for example, can recur much less frequently than every 1 to 2 years in dry climates and more frequently in wet climates. Even within the same climatic region, the flow associated with a consistent channel feature, such as top of the banks, can vary by a factor of two between different channel segments, as illustrated by studies from regions as diverse as Puerto Rico (Pike and Scatena 2010) and snowmelt-driven rivers in the Colorado Rocky Mountains (Segura and Pitlick 2010). In summary, using a morphological definition of bankfull, such as a flow that fills a channel to the top of the banks, can result in discharges with different recurrence intervals because such a flow can occur every year in some channel segments, but perhaps only once in 10 or 20 years in other channel segments. Design discharges based on recurrence intervals can thus result in very different flow magnitudes than design discharges based on channel geometry.

A third complication with bankfull discharge is that, whether defined based on channel geometry or recurrence interval, bankfull discharge does not necessarily equate to the flow that transports the majority of suspended sediment. Suspended sediment, which is composed of sediment grains sufficiently small to be carried in suspension within the water column, can originate from upland sources or via erosion of the channel bed and banks. For rivers in which much of the suspended sediment comes from erosion of the channel boundaries, bankfull discharge may not transport the majority of suspended sediment if the channel has boundaries resistant to erosion, such as channels formed in bedrock or boulders. Only very large and infrequent floods may be capable of mobilizing the boulders that form the surface of these channels (Pickup and Warner 1976; O'Connor et al. 1986; Turowski and Rickenmann 2009), thereby exposing the finer sediment beneath the boulders.

Figure 13. Interannual variability of flood peaks declines with increasing precipitation. Data points come from major rivers around the world, as illustrated by the data point labels.



2.5 Dominant and effective discharge

The concept of dominant discharge assumes that there exists a single flow magnitude that, if sustained, will maintain consistent channel geometry (Crowder and Knapp 2005). This idea evolved from the early work on bankfull discharge; dominant discharge is frequently equated to bankfull discharge. Dominant discharge is also sometimes referred to as the channel-forming flow.

Dominant discharge can be quantified in at least three ways (Table 3). First, dominant discharge can be defined as the flow that transports the greatest proportion of suspended sediment when averaged over some time interval that is typically greater than a year (Benson and Thomas 1966; Ferro and Porto 2012). This definition, also known as the flow that performs the most geomorphic work, dates to the analysis of stream gage data by Wolman and Miller (1960). Second, dominant discharge can be defined as the flow that transports the greatest proportion of bedload or total sediment when averaged over some time interval greater than a year (Mao et al. 2005; Barry et al. 2008; Bunte et al. 2014). Third, dominant discharge can be defined as the flow that is most responsible for shaping channel geometry, which is also described as the flow that is most geomorphically effective (Wolman and Gerson 1978). The first and second definitions of dominant discharge, which are based on sediment transport, are closely related to the concept of effective discharge. Effective discharge is most commonly defined as the discharge that transports the largest amount of sediment over time (Schmidt and Morche 2006), whether that be suspended sediment, bedload, or total sediment load.

Bankfull discharge, effective discharge, mean annual discharge, and the 1.5-year flow have all been proposed as constituting dominant discharge (Rosgen and Silvey 1996; Griffiths and Carson 2000). There are two fundamental problems with most of these definitions of dominant discharge. The first is that any definition based on flow level (bankfull defined in terms of channel geometry) or recurrence interval does not adequately describe all rivers. There will always be large numbers of exceptions, such as ephemeral or incised channels in arid environments or cobble-bed channels for which a flow that fills the channel to the banks or that occurs on average once every 1 to 2 years does not transport the most sediment or predominantly shape channel geometry (Emmett and Wolman 2001; Phillips 2002; Surian et al. 2009; Bunte et al. 2014; Hassan et al. 2014).

The second and more fundamental problem with dominant discharge is that form and process in natural channels reflect the entire range of flows and their history of occurrence (e.g., Heritage et al. 2001; Lenzi et al. 2006). The idea that a single magnitude of flow strongly dominates river process and form is an extreme simplification of the complexity of interactions among water, sediment, and channel geometry through time (Figures 14 and 15). As Wolman and Gerson (1978) recognized, channel form reflects the combined effects of erosional and depositional processes during flows of varying magnitude and processes, such as growth of riparian vegetation and soil formation that can act to stabilize channel boundaries. This consideration can be important in the context of delineating an OHWM because erosional and depositional features associated with flows of varying magnitude and recurrence interval can persist, making determinations of which features represent “ordinary” high water challenging. Despite the complex interactions that actually shape river channels, some measure of dominant or effective discharge is widely used in river restoration as an index value for designing channel dimensions (Barry et al. 2008).

Table 3. Definitions of dominant and effective discharge in the scientific literature.

Definition of dominant and/or effective discharge	Reference
The effective discharge is the discharge or range of discharges that transports the largest proportion of the annual suspended-sediment load over the long term.	Wolman and Miller (1960)
". . . a time scale for effectiveness may relate the recurrence interval of an event to the time required for a landform to recover the form existing prior to the event. . . . Measured recovery times . . . vary from less than a decade for some tropical regions to decades or more in temperate regions. . . . Effectiveness then is here defined in terms of the ability of an event or combination of events to affect the shape or form of the landscape."	Wolman and Gerson (1978)
"The effective discharge is defined as the increment of discharge that transports the largest fraction of the annual sediment load over a period of years."	Andrews (1980)
Effective discharge for bedload is that "which transports more bedload than any other."	Emmett and Wolman (2001)
Dominant discharge is the flow magnitude that, if sustained, will maintain the same average dimensions and channel morphology as those that result from a stable stream's entire hydrologic regime.	Crowder and Knapp (2005)
"Dominant discharge is described as the discharge of a stream that is associated with the maximum sediment-transport rate for specified magnitude and frequency of flow; as such it is a theoretical discharge representing the single flow rate of a stream that accomplishes the most geomorphic work during an extended period of time. The term is an extension of the bankfull-discharge concept and is commonly inferred to be the maximum flow that the channel of an adjusted perennial stream can convey without causing spillage onto the flood plain. When applied to the adjusted perennial streams for which it was defined, dominant discharge may have geomorphic significance, but when applied to intermittent- and ephemeral-stream channels formed by reduced rates of precipitation, runoff, and streamflow, the concept is of questionable value and may be inappropriate."	Osterkamp (2008)
". . . [we] develop an alternative metric, the functional-equivalent discharge Q_{fed}, which is the discharge that will reproduce the magnitude of the sediment load generated by the full hydrologic distribution."	Doyle and Shields (2008)
"The concept of dominant, channel forming, or most effective discharge is firmly established in fluvial geomorphology and hydraulic engineering literature. There are three main classes of definitions: (1) dominant discharge defined as the natural bankfull discharge; (2) dominant discharge defined as a discharge with a particular recurrence interval; and (3) dominant discharge defined as the discharge that transports the maximum quantity of sediment (e.g., mean annual flood)."	Hassan et al. (2014)
". . . channel forming or dominant flow, which determines and maintains the channel dimension . . ." ". . . the effective discharge, which is the flow that carries the highest sediment volume over time . . ."	Modrick and Georgakakos (2014)
". . . the stream flow that transports the largest amount of sediment over the long run. That flow is referred to as effective discharge (Q_{eff})…"	Bunte et al. (2014)

Figure 14. The North Fork Poudre River in Colorado flows through a bedrock-bounded canyon with alluvial fill. Base flow is needed to maintain populations of periphyton, aquatic insects, and fish in the river; but base flow is not capable of mobilizing the cobble-gravel bed sediment. Annual snowmelt peak flows are needed to winnow sand and silt from among the coarser bed-sediment in riffles and to maintain spawning habitats for fish, to scour sand and silt that accumulate in pools during base flow, and to maintain the pool-riffle sequence; these flows reach the *lower dashed line* or the level between the dashed lines. Periodic higher snowmelt flows are also needed to create local bank erosion that removes senescent riparian vegetation and provides germination sites for new seedlings; these flows reach the *upper dashed line*. At longer intervals, rainfall-generated flash floods also inundate the terrace surface above the *upper dashed line*, maintaining a riparian zone across the valley bottom. This river is now regulated by a dam upstream; and in the absence of periodic peak flows, xeric upland vegetation is encroaching on the channel, as seen in the juniper growing beside the active channel at the middle left in this view. The *white arrow* indicates flow direction.

Figure 15. The Colorado River in the Grand Canyon. Bedrock canyon walls and streambed constrain the overall valley geometry, but interactions between flow and sediment strongly influence the local configuration of the river. In this view upstream, the *oval* at the *upper right* indicates a backwater channel that provides critical habitats for endangered native fish. The *oval* at the *lower left* indicates the junction of an ephemeral tributary that laterally constricts the river by creating an alluvial fan and associated rapid. Base flow in the river can mobilize sand along the bed and banks, but periodic higher flows are needed to maintain the sand bars that create backwaters and to erode the lateral constrictions created by tributary fans.

2.6 Environmental flows

The simplifying assumptions underlying concepts such as bankfull and dominant discharge have been carried over into river management in the context of instream flows, channel maintenance flows, environmental flows, and river restoration (Kondolf et al. 2001; Rosgen 2006). The concept of instream flows developed as a tool to preserve some minimum flow within a channel rather than allowing all of the flow to be diverted for consumptive uses outside the channel. Initially applied in the context of fisheries (Bovee and Milhous 1978; Stalnaker et al. 1995), instream flows focused on the minimum discharge needed to preserve features such as water temperature, longitudinal connectivity, or pool volume for overwintering fish.

River management focused on minimum instream flows was broadened to channel maintenance flows once it became clear that periodic high flows are also necessary to perform functions such as scouring pools, winnowing fine sediments from the bed, or limiting channel narrowing through encroachment of riparian vegetation. Channel maintenance flows are typically defined as the components of a river's flow regime necessary to maintain specific physical characteristics, such as sediment transport, channel cross-sectional area, or pool-riffle sequences, or as the flows that move all sediment supplied to the channel and thus maintain conveyance (Leopold 1992; Emmett 1999). Channel maintenance flows are the applied equivalent of bankfull, dominant, or effective discharge. Channel maintenance flows can specify a particular magnitude and frequency of flow to achieve a particular objective, such as pool scour, or a broader range of flow magnitudes that maintain a physically diverse channel (Andrews and Nankervis 1995).

The changed emphasis within river management from instream flows to channel maintenance flows continued into the concept of environmental flows (Richter et al. 2012; Sanderson et al. 2012). The idea of environmental flows became much more widespread during the first decade of the twenty-first century (Tharme 2003). Environmental flows include experimental releases from dams (e.g., experimental floods from Glen Canyon Dam—Konrad et al. 2011; Melis 2011; Olden et al. 2014) and specified magnitude, frequency, timing, duration, and rate of change in flow of the annual hydrograph of a flow-regulated river (Arthington et al. 2006; Rathburn et al. 2009; Shafroth et al. 2010; Richter et al. 2012). The use of environmental flows as a management tool grew from the recognition that river process, form, and biotic communities are adapted to the natural flow regime (Poff et al. 1997) and natural sediment regime (Wohl et al. 2015) of a river so that management designed to sustain river ecosystems must identify and protect the multiple components of the river's hydrograph necessary to sustain channel geometry and biotic communities. The concept of environmental flows is described here as part of explaining the contemporary understanding of varying magnitudes and return intervals of flow within river science and providing a larger context for the concepts of the OHWM and the active channel.

2.7 Bankfull, dominant, and effective discharge in relation to the OHWM and the active channel

The definitions listed in Tables 1, 2, and 3 suggest the substantial overlap that currently exists between usage of the terms *active channel* and *bankfull*, *dominant*, and *effective discharge*. Active channel is most commonly defined based on channel morphology and is typically meant to indicate that portion of a valley bottom that is regularly covered by water flowing within channels. This may or may not equate to the top of the channel banks. In this sense, the boundaries of the active channel are similar to the channel as defined by the OHWM. However, in a scenario in which an extraordinary flood creates erosional and depositional features that persist and that are not colonized by woody vegetation, the active-channel boundaries can be higher in elevation than the OHWM. Bankfull discharge is also most commonly defined based on channel morphology and is used to indicate the maximum water-surface elevation at which flow is still contained within channels as opposed to spreading across a floodplain; bankfull discharge thus equates to the top of the channel banks. In many rivers, the elevation of bankfull discharge coincides with the lateral boundaries of the active channel and the elevation of the OHWM. The bankfull level is most likely to equate to the OHWM in rivers with relatively low hydrologic variability and in channels that have not been altered through river engineering. Under these conditions, the bankfull level is a persistent morphologic form that is relatively easy to define. The top of the banks also reflects a natural morphologic threshold separating areas with primarily erosional or transport sediment processes within the channel from primarily depositional processes outside of the channel. In contrast, the bankfull level is unlikely to equate to the OHWM in deeply incised channels and many intermittent and ephemeral rivers. Dominant and effective discharges are typically defined in terms of quantity of sediment transport, which may or may not correspond to a flow that just reaches the top of the channel banks.

2.8 Channel heads and stream heads

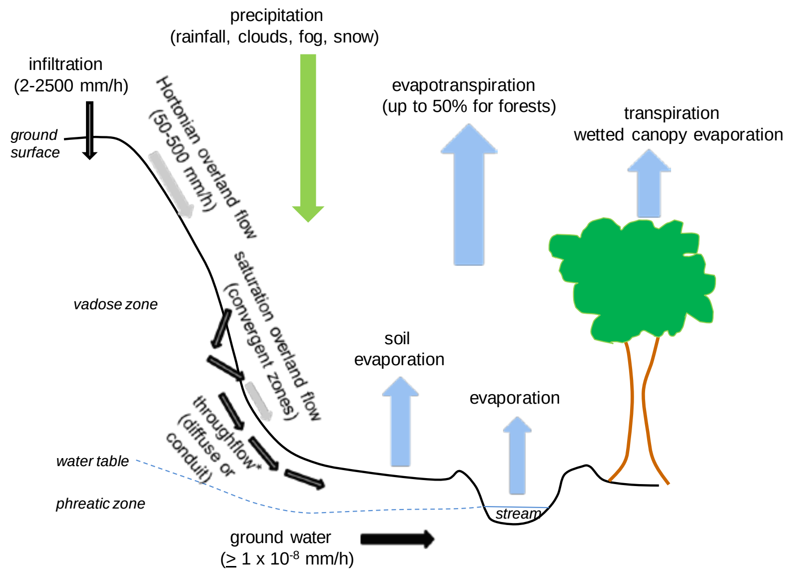
The upstream-most extent of any channel can be delineated at the channel head. Hydrologists and geomorphologists define the channel head as the upstream boundary of concentrated water flow and sediment transport on a distinct bed and between definable banks that are longitudinally continuous downstream (Montgomery and Dietrich 1988, 1989; Wohl 2014c).

This is not the regulatory definition, however; natural breaks, such as wetlands in line with a river or an alluvial fan across which the channel boundaries become diffuse, and human-caused breaks, such as pipes or dams, do not necessarily remove a river segment from CWA jurisdiction simply due to discontinuous bed and banks.

A channel head is the upstream boundary between hillslopes and channel networks. Hillslopes are characterized by downslope movement of water that can occur as unchannelized flow at the surface (sheet wash), concentrated flow at the surface that does not create a definable channel bed (rills), or subsurface flow that is diffuse (matrix flow) or concentrated within preferential flow zones (pipes and macropores) (Figure 16). Downslope movement of sediment on hillslopes can occur via the movement of individual grains or the mass movement of sediment aggregates in the form of debris flows or landslides (Figure 17). Hillslopes are spatially heterogeneous, and both water and sediment moving gradually downslope can accumulate in concavities that are known as colluvial hollows or zero-order channels. Although colluvial hollows are important sites for concentrating surface and subsurface flow and thus influence the locations of channel heads, colluvial hollows do not include channels (Dietrich and Dorn 1984; Marron 1985). If a channel head migrates upstream into a colluvial hollow, that area becomes part of the channel network and is no longer designated as a colluvial hollow.

A stream head is sometimes distinguished from a channel head as the upstream-most point in a channel at which perennial flow occurs and persists downstream (Figure 18). The channel head and the stream head can coincide but do not always do so; channel segments of ephemeral and intermittent flow can be present upstream from the stream head and below the channel head even in wet regions (Jaeger et al. 2007).

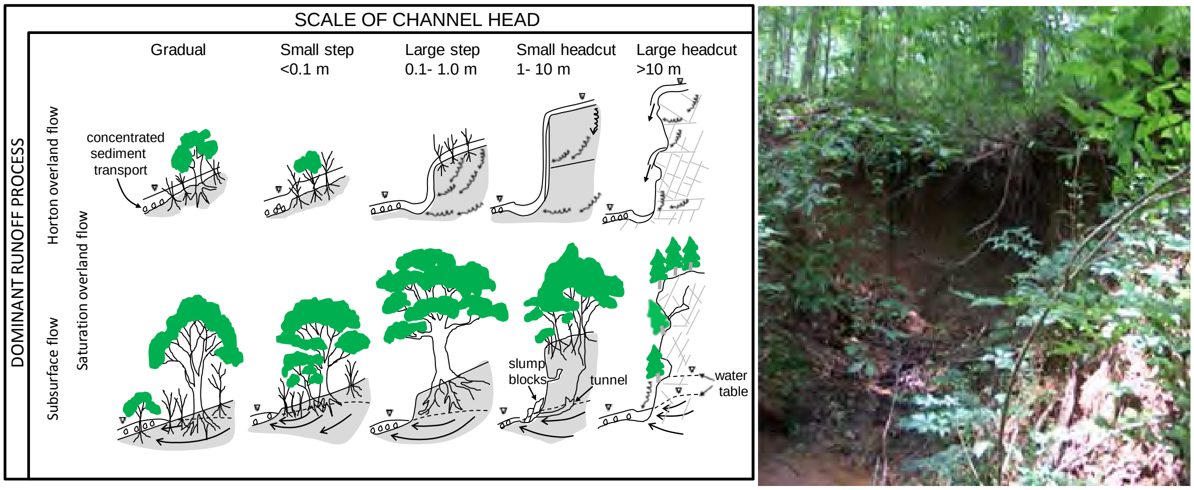
Figure 16. Schematic illustration of fluxes of water at and near Earth's surface, including downslope surface and subsurface flow paths into river channels.



* pipe flow 50-500 mm/h; diffuse flow 0.005-0.3 mm/h

Figure 17. Examples of downslope movement of sediment: at *left*, debris flow in the Colorado Rockies; *upper right*, deformation of tree trunks indicating gradual downslope soil creep; and *lower right*, debris flow in Idaho (road at lower portion of photo provides scale).

Figure 18. Illustration of different types of channel heads (after Wohl 2014c, Fig. 3.6) and an abrupt channel head on a stream near Athens, Georgia.



The locations of individual channel heads in even a small channel network can have substantially different drainage areas because of the multiple factors that influence the location of any particular channel head, including hillside gradient; drainage area; infiltration capacity; and porosity, permeability, and cohesion of the hillslope sediment. Each of these factors affects the ability of water to move through or across near-surface materials and to erode those materials and to create a channel. The location of a channel head can also vary through time as a result of changes in precipitation, land cover, and land use that affect runoff, infiltration, sediment supply, and surface erodibility (Montgomery and Dietrich 1992). A wildfire that kills vegetation and burns the surface layer of litter and duff on forested hillslopes, for example, can reduce infiltration and enhance surface runoff, causing channel heads to migrate upslope and form at drainage areas two orders of magnitude smaller than pre-fire drainage areas (Wohl 2013a). Human-induced changes in land cover can also alter the location of channel and stream heads by changing infiltration and runoff, with the most common scenario being decreased infiltration and smaller drainage areas for channel and stream heads (Montgomery 1994).

The distribution of channel heads across a river network can reflect primarily surface runoff, subsurface flow, some combination of the two, or mass movements such as debris flows or landslides (Wohl 2014c). Channel heads that form primarily via concentration of surface runoff are typically described using an empirical relation of the form

$$AS^a \geq C$$

where

A = drainage area,
S = hillslope gradient,
C = the channel initiation threshold, and
A = an empirically determined exponent that varies between sites (Dietrich et al. 1992, 1993).

Substantial variability in C between individual channel heads reflects the influence of vegetation, slope aspect, substrate grain size, bedrock fracture density, and other variables that control the relative importance of surface and subsurface flow paths (Montgomery and Foufoula-Georgiou 1993; Prosser et al. 1995; Istanbulluoglu et al. 2002; Jaeger et al. 2007; Yetemen et al. 2010).

2.9 Summary

Hydrologists and geomorphologists have worked for decades to understand how flows of differing magnitude and frequency influence channel geometry and sediment transport. This work has important implications for the concepts of an OHWM and active channel because the large body of scientific literature now in existence clearly demonstrates that "ordinary high water," defined with respect to a relatively short recurrence interval, will vary significantly between channels. Ordinary high water might be the 1- to 2-year flood in a perennial river with a humid temperate climate and relatively low interannual variability in stream flow. In this type of river, the OHWM is more likely to coincide with the boundaries of the active channel. Ordinary high water might be a 10-year flood in an ephemeral river with an arid climate and substantial interannual variability in stream flow, and the OHWM might be lower than the active-channel boundaries if these boundaries are created by a 50-year flood. As a broad generalization, large-magnitude, infrequent flows are more likely than relatively frequent flows to strongly influence channel geometry in rivers formed in materials such as bedrock, boulders, and cobbles, which require high levels of flow energy before they erode, and in rivers with greater year-to-year variability in flood magnitude (Whiting et al. 1999).

3 Delineating the OHWM

There are three primary categories of well-known and studied indicators that are currently used to delineate the OHWM: hydrologic, geomorphic, and vegetative. Hydrologic analysis relies on recurrence intervals to estimate ordinary high water and the likely elevation of the OHWM in a river, whereas geomorphic and vegetative approaches use physical or botanical features along the river to define the OHWM.

3.1 Hydrologic indicators

Hydrologic indicators derive from an analysis of the magnitude and frequency of flow at a specific site. Where systematic discharge measurements exist, such as at a stream gaging site, these data can be used with a flow-duration or flood-frequency analysis to estimate the recurrence interval of any specified discharge or the discharge that equates to a specified recurrence interval (Figure 19).

Where systematic discharge data do not exist or are of very short duration, regional discharge–drainage area equations can be used to infer flow magnitude–frequency relations at a site (e.g., Harman et al. 1999; Surian and Andrews 1999; Segura et al. 2013). The U.S. Geological Survey has published regional discharge–drainage area equations for differing magnitudes of flow for most of the United States (e.g., Sherwood and Huitger 2005; Krstolic and Chaplin 2007; Foster 2012). These equations are based on stream gage data from multiple locations within a geographic region, which are used to develop regression lines between drainage area (and sometimes elevation) and discharge. The discharge magnitude associated with a specific recurrence interval can be used with channel geometry to numerically model the flow level of the OHWM. Regionalized discharge estimates for specific recurrence intervals, such as the 2-year, 5-year, or 10-year flow, can also be accessed online for most states through the U.S. Geological Survey's StreamStats website (http://water.usgs.gov/osw/streamstats/). Commonly, a flow that recurs once every 1 to 2 years has been used to define the OHWM (e.g., Bradley and Simons 1990). This approach, however, may not be justified in some locations because of the geographic variability in the significance of recurrence intervals, as discussed earlier. Consequently, even if the hydrologic record is complete and stationarity is not an issue, questions persist as to what recurrence interval of flow to associate with the OHWM; it is a poor assumption to use the same recurrence-interval flow across all locations.

Figure 19. Examples of (*A*) flow duration curves for snowmelt in a semiarid region (Big Thompson River), rainfall in an arid region (Muddy River), rainfall in the tropics (Wailuku River), rainfall in a humid temperate region (Hatchet Creek), and snowmelt and rain in a humid temperate region (Hocking River) sites and (*B*) flood-frequency curves for the same sites. Data come from U.S. Geological Survey gages. Flood frequency is calculated using the Weibull equation (recurrence interval = [*n* + 1] / *m*, where *n* is number of years of record and *m* is rank of each discharge value from largest to smallest).

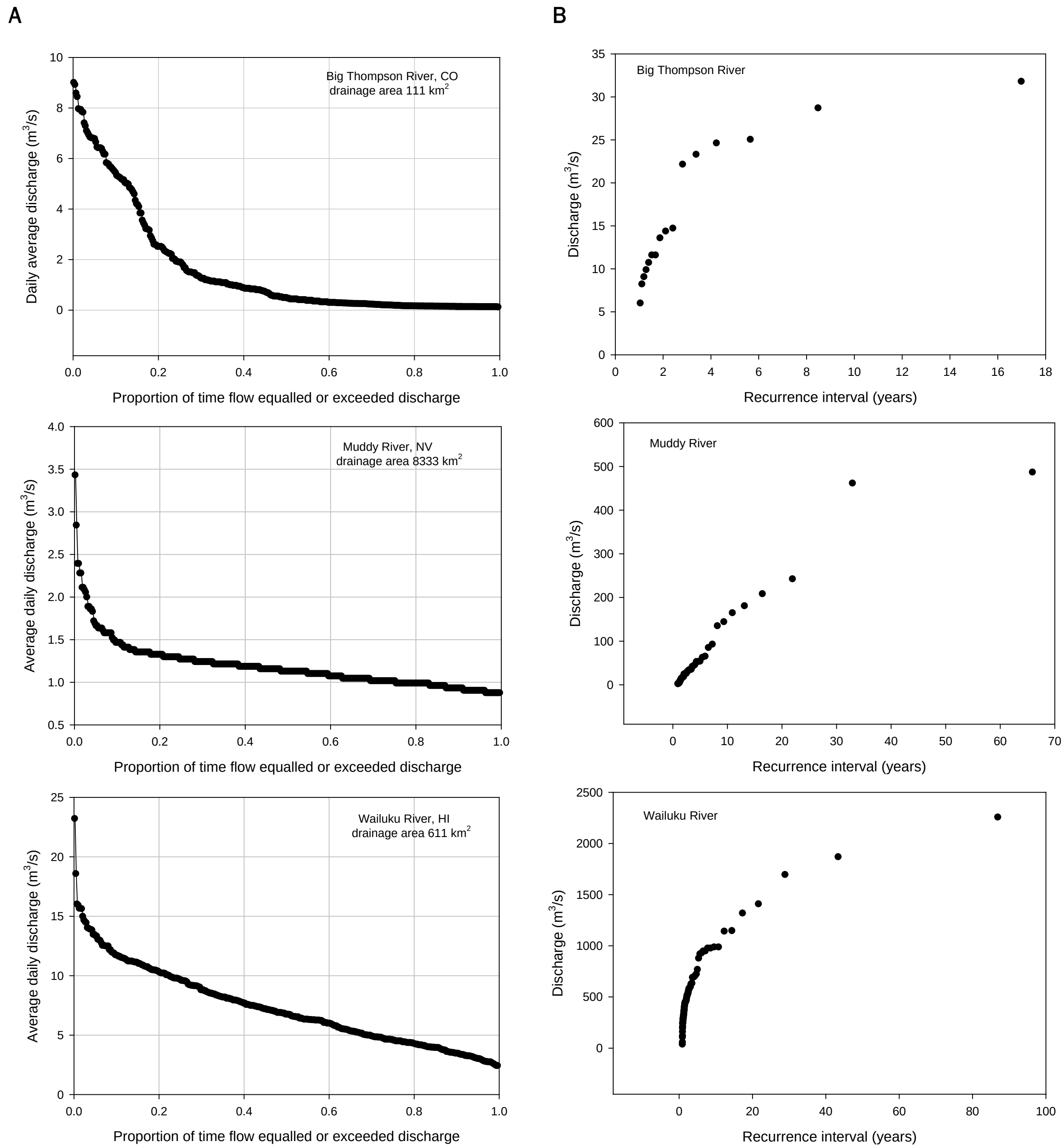
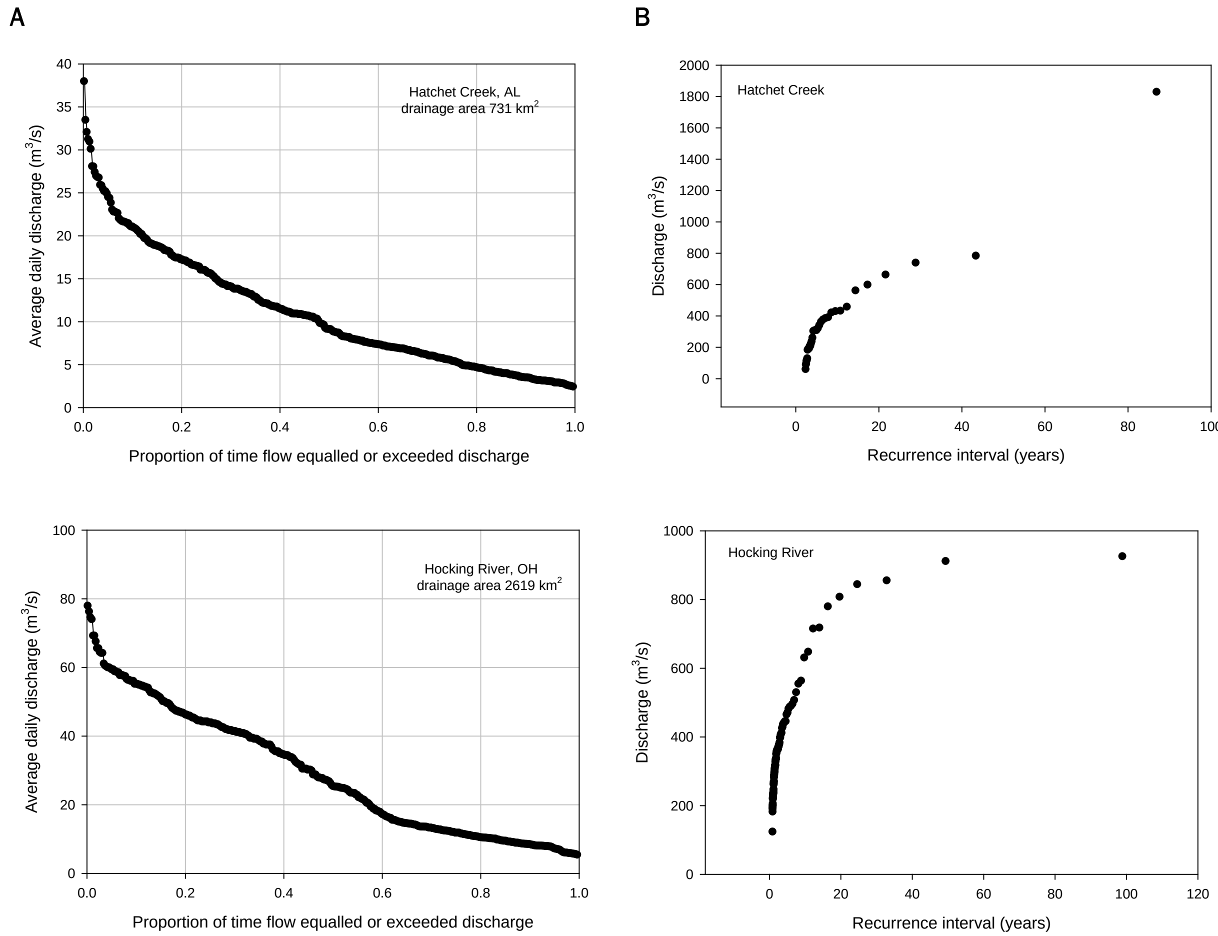


Figure 19 (cont.). Examples of (*A*) flow duration curves and (*B*) flood-frequency curves for the same sites.



A significant complication in using discharge measurements from a specific site or in using regional regressions arises from the likely presence of nonstationarity. Flow duration and flood-frequency analyses commonly rely on the assumption of stationarity in the discharge data. Stationarity is the idea that natural systems fluctuate within an unchanging envelope of variability, which implies that a variable such as annual flood peak can be accurately estimated from systematic records (Milly et al. 2008). This is a convenient assumption, but abundant evidence indicates that it is an incorrect assumption (Milly et al. 2008; Haucke and Clancy 2011).

There are three primary reasons that discharge records do not exhibit stationarity. First, climatic circulation patterns as diverse as the zonal or meridional nature of the jet stream (Hirschboeck 1987a), the El Niño-Southern Oscillation (Ely et al. 1993), and the Pacific Decadal Oscillation (Neal et al. 2002) create decadal-scale fluctuations that strongly influence the magnitude and frequency of diverse types of floods across the United

States. Systematic discharge records of sufficiently long duration to capture these fluctuations are relatively rare. This means that estimates of flood magnitude in relation to frequency by using systematic records likely do not accurately represent either long-term average values or any particular portion of multi-decadal variations.

Second, the assumption of stationarity is incorrect because changes in rainfall-runoff relations or channel conveyance within a river network can alter the magnitude and frequency of flow resulting from precipitation. These changes are associated with all aspects of human activities, from changes in land cover across a drainage basin to engineering within channels, as reviewed in more detail later in this report.

Finally, stationarity is a poor assumption because of ongoing climate change and associated alterations in precipitation patterns across the United States (e.g., Woodhouse et al. 2006). As new records are continually established for extremes of temperature and precipitation, the idea of extrapolating estimates of future flood magnitude and frequency based on measurements of past floods becomes increasingly tenuous (Barnett et al. 2005; Held and Soden 2006; Rosenberg et al. 2010).

The problem of nonstationarity can also affect field-based marks of ordinary high water, such as geomorphic and vegetative indicators.

3.2 Geomorphic indicators

Geomorphic indicators are physical features along a channel that result from erosion and deposition during ordinary high water. For example, in the case of Hayes v. State (1973),* the court defined the OHWM as “where the presence of water was so usual and continued as to mark upon the bed a character distinct from the bank in respect to vegetation and the nature of the soil itself” (Field 2004). Physical features that result from ordinary high water can include several types of erosional and depositional features. Along rivers where ordinary high water is not obvious, diverse features that typically occur below, at, and above the OHWM can be used to constrain the elevation range for ordinary high water (Table 4).

An important caveat with respect to all of the features listed in the next sections as occurring at or below the OHWM is that analogous features can

* Hayes v. State (Fencing on Navigable Waters). 1973. 496 S.W. 2D 372–375 (Arkansas).

be created above the OHWM mark during extraordinary floods. In other words, individual geomorphic features can be ambiguous with respect to any specific flood frequency and may simply characterize the last high water, whether ordinary or extraordinary.

Table 4. Potential geomorphic indicators of the OHWM categorized by location below, at, and above ordinary high water (OHW) (modified from Lichvar and McColley 2008, Table 5).

Below OHW	At OHW	Above OHW
Instream bedforms (ripples*, dunes*, lower elevation of point bars or alternate bars, longitudinal gravel bars, stepped bed morphology)	Grain size (changes in particle size distribution*, upper limit of sand-sized particles*, silt deposits*)	Weathered clasts or bedrock (desert pavement, rock varnish, clast weathering, salt splitting, carbonate etching, caliche, surface color/tone)
Evidence of bedload transport within the channel (gravel sheets to rippled sands*, sand tongues*, flaser bedding*, harrow marks*, cobble bars behind obstructions*, armored mud balls*, imbricated clasts*)	River deposits (staining of rocks, organic litter* [leaves, needles, twigs], large wood*)	Soil development
Evidence of river erosion within the channel (obstacle marks*, scour holes downstream of obstructions*)	River erosion (exposed root hairs below intact soil layer*; lower limit of valley-side soil or colluviums*; lateral truncation of alluvial fans, terraces, or rockfall deposits*)	Surface topography (relief, rounding, depositional topography, secondary drainage development)
Mudcracks*	Channel morphology (top of point bars, highest surface of mid-channel bars, break in bank slope*)	
Narrow berms and levees*	Valley-bottom morphology (active floodplain, valley flat)	
Knickpoints*		

*indicates features that can also occur on the floodplain as a result of overbank flow

3.2.1 Features below the OHWM

Basic categories of physical features that commonly occur **below** the OHWM include the following.

Instream bedforms (Figure 20)—depositional features spaced at regular downstream intervals and formed within the active channel and below the OHWM—can be indicators when in the form of

- ripples and dunes of pebble- or sand-sized sediment;
- the lower elevation portion of longitudinal bars, alternate bars, or point bars (each type of bar can be composed of sediment from silt and clay size to boulders); and

- stepped bed morphology where steps are channel-spanning, relatively short (< 1 m) vertical drops associated with cobbles and boulders, bedrock, or large wood that occur in sequence along a channel (i.e., there are multiple steps).

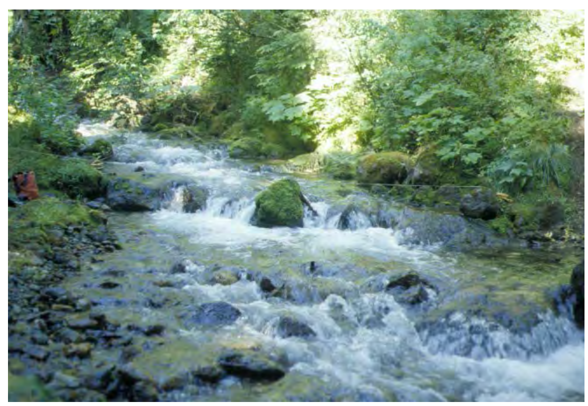
Figure 20. Examples of instream bedforms.

Ripples below the OHWM exposed on the bed of an ephemeral channel in New Mexico.

Dunes exposed on a bar along the Yukon River, central Alaska, during low flow.

Bars along the Wulik River in southwestern Alaska.

Steps along a channel in northwestern Montana.



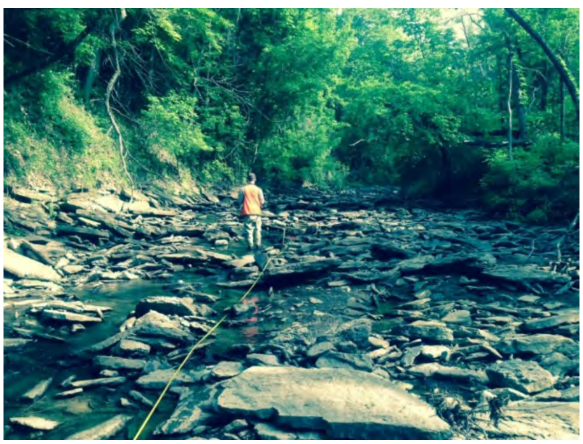
Evidence of *bedload transport* within the channel (Figure 21) can be an indicator when in the form of

- gravel sheets to rippled sands (broad, planar sediment deposits left as flow wanes);
- sand tongues (elongated planar sediment deposits left as flow wanes);
- flaser bedding (ripple bedding in which mud streaks are preserved in the troughs);
- harrow marks (sand ridges aligned in the flow direction);

- cobble bars behind obstructions (sediment can be deposited in the low-velocity zone downstream from an obstruction such as a logjam, rooted, woody vegetation, or large boulder);
- armored mud balls or rip-up clasts (can occur in ephemeral channels when silt and clay deposited during the waning stage of flow dry into a cohesive surface layer that is ripped up during the rising stage of the next flow, transported some distance downstream as cobble- to boulder-size bedload, and then deposited as flow once again wanes in the channel); and
- imbricated clasts (individual cobbles and boulders are stacked against one another with their long axes aligned parallel to flow).

Figure 21. Examples of evidence of bedload transport.

Imbricated clasts on the bed of Kain Creek, southwestern Ohio.



Imbricated clasts lodged against wood in an ephemeral channel in New Mexico.

Examples of rip-up clasts a few centimeters in diameter on a channel bed below the OHWM in New Mexico.

Sand wave that stopped moving down the bed of this ephemeral channel in southern Utah once flow receded. Camera lens cap at base of wave front for scale.

Figure 21 (cont.). Examples of evidence of bedload transport.

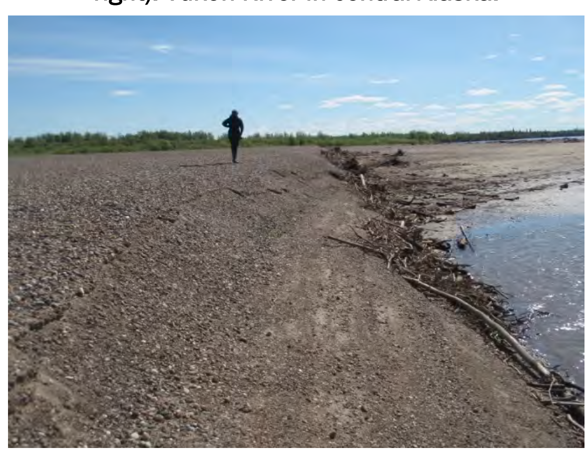
Sand waves along the bed of an ephemeral channel in eastern Colorado.

Cobbles and wood accumulated upstream of a large boulder in the bed of a steep channel (flow is from left to right).

Flaser bedding, in which very fine sediment and organic matter are trapped in the troughs between ripple crests.

Harrow marks (sand ridges aligned parallel to flow).

Example of a very thick gravel sheet that was mobile during the last high flow, as evidenced by the steep, downstream front seen there (flow direction left to right). Yukon River in central Alaska.



Evidence of *river erosion* within the channel (Figure 22) can take the form of

- obstacle marks (erosional or depositional features downstream from an obstacle such as a large boulder, bridge pier, or rooted, woody vegetation) and
- scour holes downstream of obstructions (formed by horseshoe vortices that form downstream from an obstruction such as a large boulder; bridge pier; or rooted, woody vegetation).

Figure 22. Examples of erosion within the channel. Obstacle-induced upstream scour and downstream deposition, here around bedrock knobs protruding through a sand layer (flow is left to right).

Narrow berms and levees (Figure 23) are longitudinal (oriented parallel to flow) deposits along the margins of the channel resulting from reduced energy for sediment transport and can occur below or at the level of the OHWM.

Figure 23. Examples of narrow berms below the OHWM along channels in central Arizona. In each case, the berm lies below the *upper dotted line*, which approximates the OHWM, and the *lower dotted line*.

Mudcracks (Figure 24) form by drying of silt and clay deposited during the waning stages of flow.

Figure 24. Examples of mudcracks below the OHWM on the channel bed of ephemeral channels in New Mexico.

Knickpoints (Figure 25), like steps, form within the active channel and typically below the OHWM; but knickpoints are taller (>1 m) vertical drops that can occur singly or in sequence along a channel.

Figure 25. Examples of knickpoints present below the OHWM along an ephemeral channel in New Mexico. In each photo, the *white arrow* indicates a potential OHWM and the *yellow arrow* indicates flow direction. In the *left* photo, the *white circle* highlights a set of car keys for scale.

3.2.2 Features at the OHWM

Basic categories of physical features that commonly occur **at** the OHWM include the following.

Grain size (Figure 26) indicators can take the form of

- changes in particle size distribution (a transition from coarser to finer-grained sediment that marks the upper limit of bedload transport is likely to be at or just below the OHWM),
- an upper limit of sand-sized particles (sand can travel in suspension or as bedload and, when deposited along the channel margins as flow recedes, is likely to approximate the level of ordinary high water), and
- silt deposits (silt and clay particles travel suspended in the water column and can adhere to the channel margins as flow recedes).

Figure 26. Examples of grain-size indicators at the OHWM. Vertical changes in grain size within a river in New Mexico. The active channel (*foreground*) is a mix of cobbles and sand, with a sand bar in the middle of this view. A cobble layer forms the base of the vertical bank, with sand and silt in the upper bank.

River deposits (Figure 27) can take the form of

- staining of rocks(dissolved minerals within river flow can precipitate on rocks along the channel, typically to the elevation of ordinary high water);
- organic litter, such as leaves, needles, and twigs (fine organic matter carried on the surface of the water column is deposited along channel margins during waning flow); and
- large wood (wood pieces greater than 10 cm diameter and 1 m length are carried on the surface of the water column and deposited along channel margins during waning flow).

Figure 27. Examples of river deposits at the OHWM.

Large wood accumulated in a jam at the OHWM along a channel in north-central Colorado (flow is from left to right).

Stains left by algae growing within the channel (*pale gray*, indicated by *blue arrow*) and by the higher water level (*yellow arrow*).

A closer view of the same point along the channel reveals a windrow of finer organic matter deposited by river flow at the OHWM.

Fine organic litter forming a duff layer beneath the forest is truncated at the OHWM.

River erosion (Figure 28) can take the form of

- exposed root hairs below intact soil layer (indicating the upper limit of river erosion along the banks);
- lower limit of valley-side soil or colluvium (indicating the upper limit of river erosion along the banks or valley side slopes); and
- lateral truncation of alluvial fans, terraces, or rockfall deposits (indicating the upper limit of river erosion of depositional features impinging on the channel).

Figure 28. Examples of river erosion at the OHWM.

Lower limit of hillslope colluvium along an intermittent channel in southern Arizona. Exposed bedrock is a pale gray color (hat for scale); colluvium and hillslope soil above is pale brown.

Roots exposed by erosion at the OHWM in an ephemeral channel.

Channel morphology (Figure 29) indicators can include

- top of point bars (this represents a minimum elevation for the OHWM because point bars form via deposition of bedload, which will not accumulate above the water surface),
- highest surface of mid-channel (longitudinal, alternate) bars (this represents a minimum elevation for the OHWM because bars form from deposition of bedload and this sediment will not accumulate above the water surface), and
- break in bank slope (this can indicate a commonly occurring water level).

Figure 29. Examples of channel morphologic features at the OHWM.

Point bar along Sycamore Branch in Hoosier National Forest, south-central Indiana.

Lines left by receding flow along the Yukon River, central Alaska. Top of the bank has a prominent break in slope with trees growing on relatively flat surface above bank.

Bar top exposed during low water along the Black River, central Alaska.

Gravel bars exposed during low flows, southwestern Alaska.

Valley-bottom morphology (Figure 30), including the active floodplain and valley flat, can be an indicator because if the OHWM is constrained to occurring within the channel, then any portion of the valley bottom outside of the channel is at or just above the OHWM.

Figure 30. Examples of valley bottom morphology.

East Inlet Creek, Rocky Mountain National Park, Colorado.

Missouri River in Montana.

Bear Creek, northern California.

3.2.3 Features above the OHWM

Basic categories of physical features that can occur **above** the OHWM include the following.

Weathered clasts or *bedrock* (Figure 31) can take many forms:

- Desert pavement—a surface covered by tightly packed gravels or cobbles, analogous to a cobblestone street, which can form in dry regions through diverse processes occurring outside of channels
- Rock varnish—an iron-manganese coating that forms a brown or black stain on rock surfaces exposed to chemical weathering in dry environments and is not abraded by suspended sediment in river flow
- Clast weathering—evidence of mineralogical alteration of the surface of cobbles and boulders, which can be seen as a weathering rind, or outer

layer like the skin of a piece of fruit, when the clast is split open; the presence of this layer indicates exposure to weathering in the absence of abrasion by river-transported sediment

- Salt splitting—common in dry regions, a weathering process in which salt crystals grow within and wedge open cobbles and boulders sitting at the surface
- Carbonate etching—weathering of carbonate (e.g., calcite, dolomite) minerals that creates a rough surface; abrasion by fluvially transported sediment tends to remove this etching
- Caliche—reprecipitated calcium carbonate that forms a white layer below the ground surface in dry environments; prolonged soaking by flowing water, as in a river, tends to prevent or remove caliche deposits
- Surface color/tone—weathering of cobbles, boulders, and bedrock can alter the color of the rock surface relative to the interior of the rock, whereas abrasion by river water creates a surface more similar in color to the interior of the rock

Figure 31. Examples of indicators above the OHWM.

Salt splitting of a cobble on an alluvial fan outside of the channel, southwestern Arizona (keys for scale).

Disintegration of clasts as a result of weathering on an alluvial-fan surface in Death Valley, California. The piles of differently colored fine rubble are the remnants of cobbles that weathered in place.

Figure 31 (cont.). Examples of indicators above the OHWM.

The darker surface on the left side of this basalt boulder in New Mexico is desert or rock varnish. The boulder was displaced during road construction, revealing the lighter-colored surfaces that do not have desert varnish and that were formerly below the ground surface.

Early stages of caliche development, showing here as discontinuous white coating on the underside of cobbles.

During the later stages of caliche development, calcium carbonate fills all voids and creates a subsurface layer analogous to concrete in its hardness.

Desert pavement formed on an alluvial fan in southwestern Arizona.

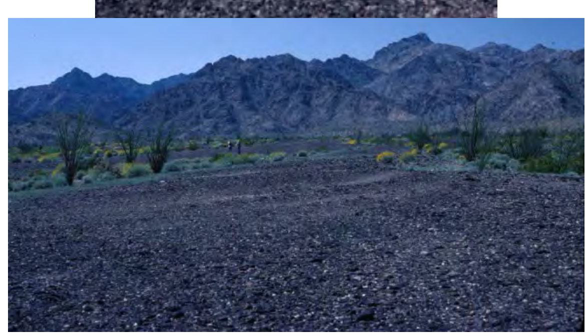


Figure 31 (cont.). Examples of indicators above the OHWM.

Carbonate etching—fine-scale erosion of the surface of limestone or dolomite—present above the OHWM, western Texas. Carbonate rocks present below the OHWM are more likely to be smoothed and sculpted by dissolution and abrasion.

Differences in surface color or tone on this alluvial fan in Death Valley, California, indicate areas of recent river erosion and deposition (lighter color) and older, stable surfaces (darker color).

Soil development (Figure 32) is another indicator as whatever the climate, development of a detectable soil with horizontal layers formed through weathering and translocation of clays, salts, and carbonates requires some minimum length of time over which the surface and near-surface sediment is stable; consequently, the presence of a soil profile implies the absence of recent river erosion or deposition

Figure 32. Soil development above the OHWM. In dry climates, soils form slowly and only on relatively stable surfaces. In this cutbank along a river in western Texas, the darker, relatively organic-rich upper layer of the bank indicates a soil that has formed in the absence of river erosion or deposition.

Topographic relief (Figure 33) is created by secondary erosion across the former floodplain or other portions of the valley bottom once these surfaces are no longer subject to active river processes. The presence of this relief indicates an absence of river erosion; examples include eolian (wind-blown) features, erosion of the surface by sheet wash, or secondary drainages eroded into the surface.

Figure 33. Examples of topographic relief and steeper hillslope gradients above the OHWM. (The *upper* photos are east of Ashland, Missouri; the *lower* photo is on the Smoky Hill River in Kansas.)

It is important to emphasize at least two points regarding the features listed above. First, not all of these features will be present along any particular river reach. Typically, some combination of erosional and depositional features can be used to determine the OHWM. Second, several of these features can occur on floodplain surfaces outside of channels as a result of overbank flow; but the features can still represent ordinary high water. These features are denoted with an asterisk in Table 4. Lichvar and McColley (2008) include numerous photographs and detailed descriptions of indicators of the OHWM that can be found in arid regions, along with a list of tools needed to identify these indicators and a description of the procedure for delineating the OHWM.

3.3 Vegetative indicators

The characteristics of vegetation along a channel (Table 5) can be used alone or in combination with geomorphic indicators to delineate the OHWM. Many species of lichen cannot survive inundation, for example; and the lowest level to which specific lichen species grow along a channel defines a lichen limit (Foulds et al. 2014) that equates to the water level of high flows (Maas and Macklin 2002; Sammut and Erskine 2013). Although most xeric or upland plants are intolerant of being inundated by water, aquatic and riparian plants have adapted to continual or periodic inundation and to the physical damage (erosion of soil around the roots and battering or breakage of stems and trunks) characteristic of near-channel environments (Hupp 1988). In addition, upland annual native species of dry regions can bloom within the active portion of ephemeral channels following vernal runoff (Went 1948). Consequently, although the presence or absence of vegetation can sometimes be used to define the OHWM (e.g., Northwest RR v. United States 1943[*] defined the OHWM as the line where the water stands sufficiently long to destroy vegetation below it), the species and ages of plants present at specific elevations along a channel, particularly woody shrubs and trees, are more likely to be useful in estimating the frequency or time since last occurrence of a flow that reached a specific elevation (Hupp and Osterkamp 1985; Hupp 1988; Pike and Scatena 2010) (Figure 34). The details of which species and ages of vegetation will be useful in this context are very region specific. An example of a past court decision using this approach is Sale of Islands (1967) in which the OHWM was defined as the line of timber growth.

[*] Northwest RR v. United States (Structures Erected in Bed of Navigable Stream Subject to Destruction Without Remedy by United States in Aid of Navigation). 1943. 100 CT CL 396–413.

Table 5. Potential vegetative indicators of the OHWM categorized by location below, at, and above ordinary high water (modified from Lichvar and McColley 2008, Table 6).

Indicators	Below OHW	At OHW	Above OHW
Hydroriparian indicators (areas that are perennially saturated or inundated)	Herbaceous marsh species Pioneer tree seedlings Sparse, low vegetation Annual herbs, hydromesic ruderals Perennial herbs, hydromesic clonals	Annual herbs, hydromesic ruderals Perennial herbs, hydromesic clonals Pioneer tree seedlings Pioneer tree saplings	Annual herbs, xeric ruderals Perennial herbs, non-clonal Perennial herbs, clonal and non-clonal co-dominant Mature pioneer trees, no young trees Mature pioneer trees w/upland species Late-successional species
Mesoriparian indicators (areas that are seasonally moist)	Pioneer tree seedlings Sparse, low vegetation Pioneer tree saplings Xeroriparian species	Sparse, low vegetation Annual herbs, hydromesic ruderals Perennial herbs, hydromesic clonals Pioneer tree seedlings Pioneer tree saplings Xeroriparian species Annual herbs, xeric ruderals	Xeroriparian species Annual herbs, xeric ruderals Perennial herbs, non-clonal Perennial herbs, clonal and non-clonal codominant Mature pioneer trees, no young trees Mature pioneer trees, xeric understory Mature pioneer trees w/upland species Late-successional species Upland species
Xeroriparian indicators (dry areas)	Sparse, low vegetation Xeroriparian species Annual herbs, xeric ruderals	Sparse, low vegetation Xeroriparian species Annual herbs, xeric ruderals	Annual herbs, xeric ruderals Mature pioneer trees w/upland species Upland species
General indicators	Moss and bryophytes requiring regular submergence Adventitious sprouts Eccentric rings	Species of lichen tolerant of limited submergence and abrasion Impact scars on trees Adventitious sprouts Eccentric rings	Species of lichen intolerant of submergence and abrasion

Clonal species: a group of genetically identical individuals growing in a given location, all originating vegetatively from a single ancestor (e.g., *Populus tremuloides* [aspen] or *Salix herbacea* [dwarf willow])

Herbs: plants with little or no woody tissue

Hydromesic: soil retains water for long periods of time but will drain

Pioneer species: a species that colonizes a previously uncolonized area

Ruderal: disturbance-adapted herbaceous plant (e.g., *Chamerion angustifolium* [fireweed])

Xeric: adapted to an extremely dry habitat

Figure 34. Examples of vegetative zoning along channels from diverse environments.

Herbaceous vegetation, woody shrubs, willow, and poplar form bands successively higher in elevation and farther back from the active channel along the Wulik River in Alaska.

Herbaceous vegetation grows close to the active channel along Wailuku River in Hawaii, with woody vegetation farther up the banks.

Herbaceous and woody vegetation along a cloud forest stream in Hawaii.

Woody vegetation grows down to the margins of the active channel along the Rio Mameyes in Puerto Rico.

Rapidly growing herbaceous vegetation covers the active channel in this ephemeral channel in New Mexico. Xeric upland species such as pines and juniper grow along the margins of the active channel.

In addition to the presence or absence of specific types of vegetation at differing heights above the channel, growth irregularities of woody vegetation can be used to infer the maximum water level of both ordinary and extraordinary floods (Yanosky 1983; Ruiz-Villanueva et al. 2010). Woody vegetation can survive physical damage induced by flood waters and by debris carried in floods, but the vegetation can have growth irregularities in the form of eccentric rings, impact scars, and adventitious sprouts. Eccentric rings are asymmetrical annual growth rings that occur when a tree is hit with sufficient force to tilt the entire trunk (Figure 35A) (Yanosky and Jarrett 2002). Impact scars occur where the tree trunk is hit with sufficient force to kill the cambium, which is the growth layer just beneath the outer bark (Figure 35B) (Yanosky and Jarrett 2002). An impact scar can be visible at the surface or may be hidden by subsequent growth over the scar. Adventitious sprouts form as regrowth after a trunk is sheared off or knocked down without being completely uprooted (Figure 35C) (Yanosky and Jarrett 2002). The date at which eccentric rings or adventitious sprouts began or the date at which an impact scar occurred can be measured by coring the tree and counting the annual growth rings (Yanosky and Jarrett 2002). Because a damaged portion of a tree trunk does not grow upward with time, the top of the water surface when the damage occurred can be estimated from the height of an impact scar. This estimated water-surface elevation can be converted to a discharge estimate for the flood by using standard hydraulic equations (Webb and Jarrett 2002). Using this approach, Hupp (1988) developed a flood-frequency curve for Passage Creek, Virginia. Passage Creek also had a stream gage, allowing Hupp to confirm that the flood-frequency analysis based on botanical records accurately estimated the magnitude and water-surface elevation for floods that recurred every 1 to 2 years.

Flood damage to trees can resemble damage associated with fire, wind storms, or animals such as porcupines. Commonly, multiple scarred trees along a channel are used to develop a vegetative record of flow damage. Impact scars are present on the upstream side of riverside trees and typically have a diamond or oval shape, as opposed to fire scars, which commonly occur in triangular shapes near the base of the trunk.

Figure 35. Illustrations of vegetative HWMs. (*A*) Schematic illustration of eccentric rings exposed in a cut stump (after Hupp 1988). (*B*) Impact scars: Flood-scarred Ponderosa pine (*Pinus ponderosa*) along Rattlesnake Creek, Arizona. Two scars are visible in this photo: a larger scar at center, the base of which has been cut for tree-ring sampling, and a smaller scar at upper right. (*C*) Adventitious sprouts: A tree with two adventitious sprouts that grew after the original trunk of the tree was sheared off by flood waters, John Day River, Oregon.

A B C

Another technique for extending systematic gage records of river flow back over longer time periods is to use tree-ring records to reconstruct annual flow volumes (Woodhouse et al. 2006). This technique is particularly effective in arid and semiarid regions in which availability of moisture can limit tree growth. Although this approach primarily provides information on annual flow volume (http://treeflow.info/), it can also be used with channel cross-sectional geometry to obtain at least rough estimations of ordinary high water.

3.4 Lateral and longitudinal extent of the OHWM

The OHWM indicators discussed thus far can be used to delineate the lateral boundaries of ordinary high water at a site along a river. Many of these same indicators can also be helpful in delineating the upstream-most extent of a river channel. As noted earlier, the channel head is the upstream boundary of concentrated water flow and sediment transport on a distinct bed and between definable banks that are longitudinally continuous downstream to the presence of a persistent feature such as a wetland, alluvial fan, or lake (Montgomery and Dietrich 1988, 1989; Wohl 2014c).

The presence of a bed and banks implies that the same types of OHWM indicators present in larger channels can also be present along very small channels at the upstream extent of the river network. A key point, however, is that erosional and depositional forms scale with channel size. Point bars that can be tens of meters long and wide in a large channel, for example, can also be present in a sinuous headwater channel but may be much less than a meter in length and diameter.

One of the more difficult tasks in using OHWM indicators to delineate the upstream extent of a channel is to differentiate channel segments created and maintained by fluvial processes from channel segments dominated by non-fluvial processes, such as debris flows. Some OHWM indicators are particularly useful in this context. Fluvial bedforms, such as ripples and dunes, for example, are useful in distinguishing fluvial deposits from debris-flow sediment, which does not display bedforms. Conversely, staining of rocks or exposed root hairs can mark the upper limit of water flow (i.e., OHWM), but these indicators can also mark the upper limit of a debris-flow slurry.

4 Geographic Variations in the OHWM

As touched on earlier, the magnitude and frequency of a flow that might leave an OHWM vary substantially between sites. This section discusses how this variation relates to climate and hydrology, position within the drainage network and channel geometry, and channel substrate. Climate and hydrology govern seasonal and interannual variations in flow magnitude and partly control whether an OHWM is created by a flood that recurs every year or two, or by a flood that recurs over longer time intervals. Position within the drainage network and channel geometry govern whether ordinary high water is likely to be contained within channels or to spread beyond the channel to the floodplain. Channel substrate, by determining the erosional resistance of the channel boundaries, along with likelihood and speed of recolonization of the river banks by vegetation, governs whether the OHWM and extraordinary HWMs are likely to be transient features or to persist until the next flood of similar magnitude occurs. Extraordinary HWMs can be the same geomorphic indicators used to determine ordinary high water (i.e., erosional or depositional features or aspects of channel geometry). Along rivers with channel boundaries strongly resistant to erosion and with substantial variability in peak flows through time, the geomorphic indicators created by extraordinary floods with long recurrence intervals may persist along the river corridor. An extreme example of this phenomenon occurs in bedrock channels that experienced enormous floods of glacial meltwater at the end of the Pleistocene Epoch of geologic time. The erosional and depositional features created by these floods 10,000 to 15,000 years ago still persist along some bedrock channels (O'Connor 1993).

4.1 Variations in the OHWM in relation to climate and hydrology

Climate influences the magnitude and frequency of ordinary high water by governing (i) the type of precipitation that generates runoff and direct flow (e.g., convective rainfall and snowmelt), (ii) the annual variability in precipitation inputs (e.g., rainfall throughout the year versus strongly seasonal rainfall), and (iii) the interannual variability in precipitation inputs. Precipitation inputs governed by climate interact with drainage basin characteristics such as topography, vegetation cover, and soil infiltration capacity to govern the hydrology of a river. Snowfall on a steep, rocky drainage basin may produce primarily surface runoff and direct flow, for example, whereas snowfall on a low-relief drainage basin with well-developed soils may produce melt water that largely infiltrates and moves gradually into the river as base flow. This section examines characteristic differences in the OHWM in relation to distinct climatic regimes present within the United States and in relation to the resulting streamflow regimes.

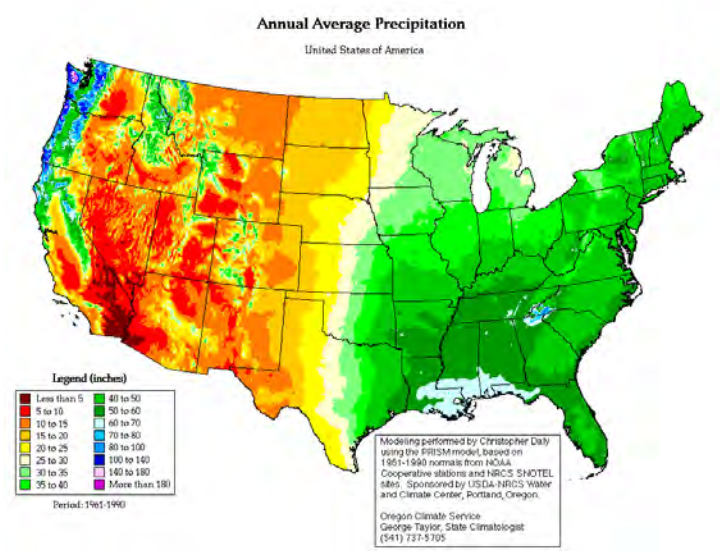
Table 6 lists the characteristics of precipitation associated with six general climate regions present in the United States Figure 36).

Table 6. Precipitation characteristics in relation to climate regions in the United States.

Climate Region	Types of Precipitation	Relative Seasonal Variability	Relative Interannual Variability
Arid	predominantly rainfall	moderate	very high
Semiarid	rainfall and snow	moderate	high
Humid temperate	rainfall and snow	moderate	moderate
Tropical	rainfall	high	moderate
Boreal	rainfall and snow	high	low
Arctic	rainfall and snow	high	low

Figure 36. Maps of annual average precipitation across (*A*) the continental United States, (*B*) Hawaii, and (*C*) Alaska. The six general climate regions referenced in this document, as defined by precipitation and latitude, are arid (less than 10 in. of precipitation), semiarid (10 to 20 in. of precipitation), humid temperate (all temperate latitudes with greater than 20 in. of precipitation), tropical (Hawaii), boreal (Alaska south of 70°N latitude), and Arctic (Alaska north of 70°N).

A



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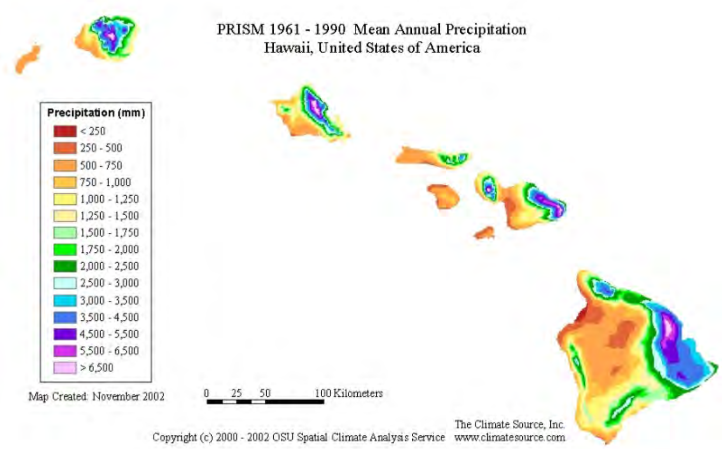

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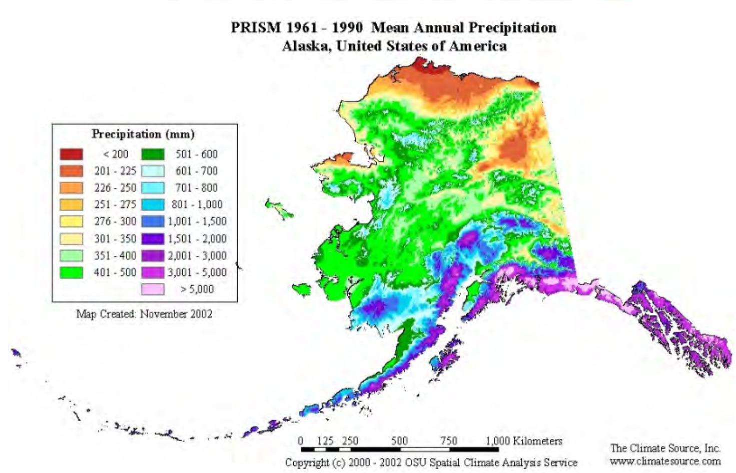


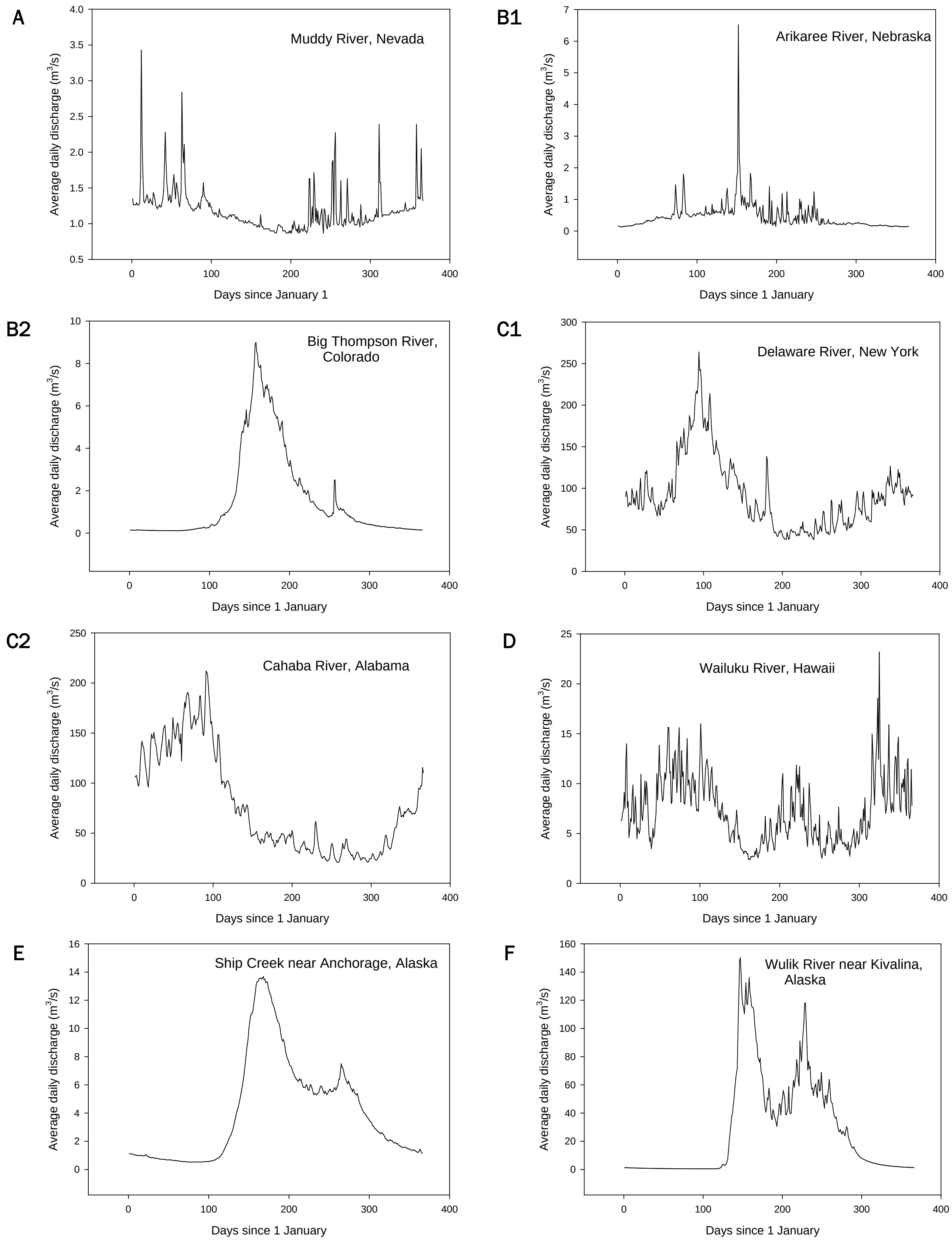
4.1.1 Arid regions

Arid regions receive less than 250 mm (10 in.) of precipitation per year and have the potential to lose more water via evapotranspiration than falls as precipitation. Portions of the western United States that receive more than 250 mm of precipitation can still be arid because of high rates of evapotranspiration that result in annual water deficits. In the United States and in the context of this classification, arid regions are hot deserts rather than polar deserts. These regions, which occur in the western United States, are characterized by the following processes and features (Graf 1988; Tooth 2013; Sutfin et al. 2014):

- Strong orographic effects on precipitation, corresponding to increased precipitation with increased elevation
- High spatial and temporal variability in precipitation
- Limited infiltration and substantial surface runoff during precipitation
- The potential for transmission losses of stream flow through evaporation and infiltration into the river bed, causing discharge to decline downstream
- Peaked flood hydrographs (short duration and large magnitude) (Figure 37A),
- A high ratio of peak-to-average annual discharge
- High interannual variability in peak flows.

Applying regional regression equations for discharge to arid-region channels in the United States is difficult because these regions typically have floods that can be caused by different meteorological patterns. The southwestern United States, for example, can have floods resulting from frontal rainfall during the winter, convective rainfall during the summer, and tropical storms during the autumn (Hirschboeck 1987b). In mountainous regions and on alluvial fans, distinguishing channel form derived from water floods versus debris flows can also be challenging (Waythomas and Jarrett 1993; O’Connor et al. 2001). Debris flows typically create distinctive erosional and depositional features, such as sharp-crested, coarse-grained levees; but experience is needed to differentiate these from flat-crested, sorted flood deposits.

Figure 37. Sample annual hydrographs from diverse climatic regions within the United States: (*A*) arid, (*B*) semiarid rainfall (Arikaree) and snowmelt (Big Thompson), (*C*) humid temperate with snowmelt (Delaware) and only rainfall (Cahaba), (*D*) tropical, (*E*) boreal, and (*F*) Arctic.



Arid-region alluvial channels are sometimes described as being in disequilibrium because they exhibit substantial changes in channel geometry in response to the high interannual variability of peak flows (Graf 1988; Tooth 2013). Numerous case studies describe channels that, over a period of several decades to a century, repeatedly alternate between meandering and braided (Burkham 1972; Jaquette et al. 2005) or between deeply incised arroyos and relatively shallow swales (Webb et al. 1991). Substantial changes in channel geometry through time can make it difficult to delineate a persistent OHWM.

Several channel classifications have been proposed for arid regions in the United States. Field (2004) distinguishes (i) discontinuous ephemeral river segments that alternate downstream between deeply incised arroyos that represent erosional zones and depositional reaches of sheetflooding; (ii) compound channels in which a low-flow meandering channel is inset into a wider, braided flood zone and the predominant channel geometry alternates through time between meandering and braided in a manner mediated by riparian vegetation; (iii) alluvial fans with distributary channels and multiple flow processes (river flow, debris flows, and sheetflooding) as well as frequent channel avulsions; (iv) anastomosing channels that are sinuous, multi-thread channels with one main channel and more fine sediment and bank cohesion than are found in braided channels; and (v) single-thread channels that are typically perennial and meandering, with relatively abundant riparian vegetation and adjacent floodplains (Figure 38). Sutfin et al. (2014) distinguish (i) piedmont headwater channels that initiate on piedmont surfaces and are formed in partially consolidated alluvium but lack significant bar or floodplain development, (ii) montane bedrock channels confined by exposed bedrock and devoid of persistent alluvium, (iii) bedrock with alluvium channels that are confined by bedrock but contain a persistent bed of active alluvium for at least half of the reach length, (iv) incised alluvium in which the channel has an active alluvial bed and partially consolidated alluvial banks, (v) braided channels that are depositional environments with multiple channels and transient bars, and (vi) depositional floodout zones where the channel becomes poorly defined or indistinct (Figures 39 and 40).

Figure 38. An example of classifications for arid-region rivers: channel morphologies characteristic of alluvial fans in the southwestern United States. Morphologic types can change with time and space (from Field 2001 and Field and Lichvar 2007, Fig. 9).

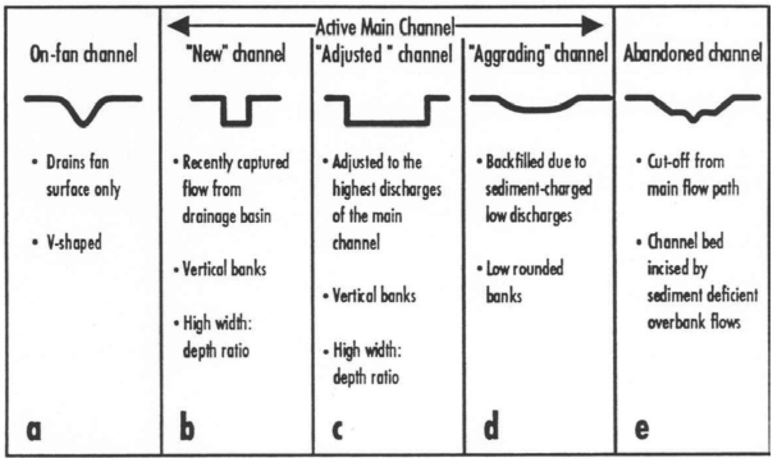


Figure 39. Five arid-region ephemeral channel types depicted as an idealized progression include primarily erosive piedmont headwater (*A*) and bedrock (*B*) channels, those located in intermediate transfer zones along the transition from the mountain front to the piedmont or adjacent to the piedmont (bedrock with alluvium [*C*] and incised alluvium [*D*]) and primarily depositional braided channels (*E*) (Sutfin et al. 2014, Fig. 2).

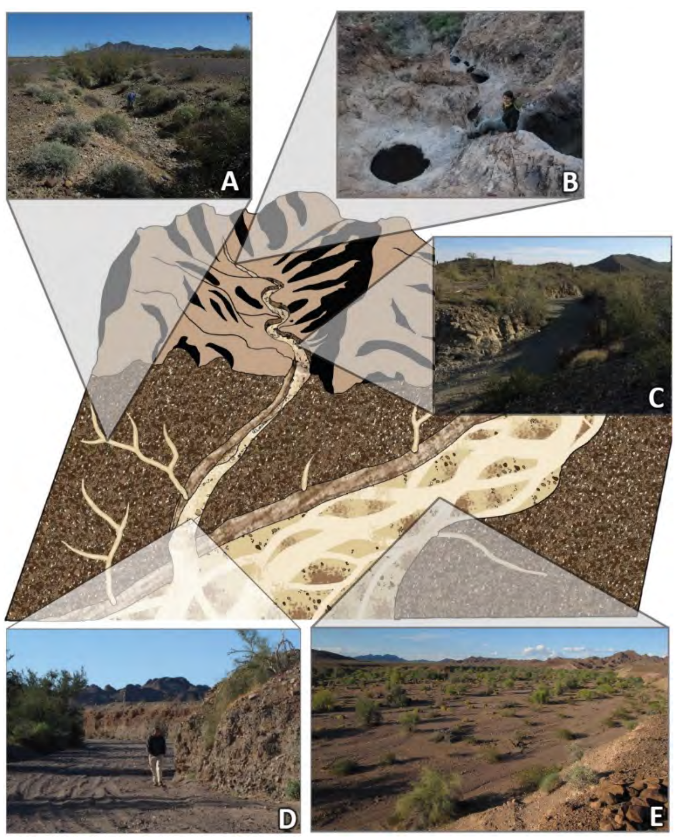
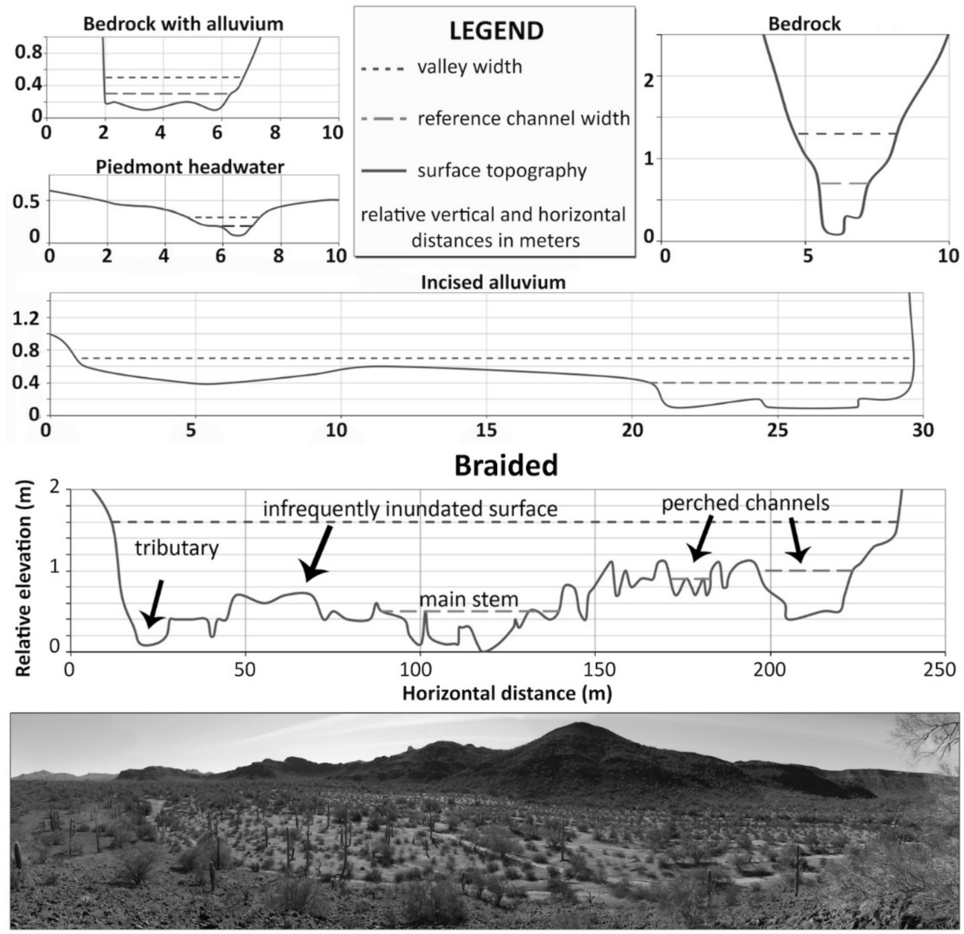


Figure 40. Representative cross-sectional profiles for bedrock, bedrock with alluvium, piedmont headwater, incised alluvium, and braided channel types. Figures are in relative scale to one another with vertical and horizontal axes in meters except for the typical cross section of a braided wash, which is at a significantly different scale (Sutfin et al. 2014, Fig. 3).



Both of these classification systems identify the number of channels as an important distinguishing feature but diverge in how they discuss the geomorphic features, Field (2004) relying on identification of the feature in the landscape and Sutfin et al. (2014) focusing on the substrate and characteristics of sediment movement. The relevance of these classifications in the context of the OHWM is that distinct channel types are likely to have different types of OHWM indicators. Alluvial channels, for example, are most likely to have indicators in the form of instream bedforms, sediment transport, changes in grain size, and soil development whereas bedrock channels are more likely to have indicators in the form of river erosion.

Lichvar and Wakeley (2004) propose the following OHWM definition for channels in arid regions:

> That part of the active channel where sediment transport is due to the most frequent or repeating hydrologic discharges, resulting in the development of bed and bank or other physical features, including vegetation, representing long-term trends in either storm or annual discharge events. This definition recognizes that, in some instances, extreme events may have developed the outermost physical features of the active channel and that the current "ordinary" limits may occur within these features."

Lichvar and Wakeley (2004, Table 1) provide a detailed list of geomorphic and vegetative indicators above, at, and below the OHWM along arid-region channels; and Lichvar and McColley (2008) provide extensive examples and a list of the tools that can be used to delineate the OHWM. Field (2004) also describes four approaches to delineating the OHWM in arid rivers, based on the geomorphically effective flow, exclusion of areas above and below the OHWM, recognition of the transitory nature of arid-region rivers, and hydrologic and hydraulic methods.

Perennial rivers in arid regions, which are commonly supplied by either groundwater inputs or snowmelt in adjacent wetter and higher-elevation regions, may be more similar to rivers in wetter climates in terms of channel morphology, stability, and creation of OHWMs than are ephemeral or intermittent rivers in arid regions.

4.1.2 Semiarid regions

Semiarid regions receive yearly amounts of precipitation that are slightly below rates of evapotranspiration. Typically, these regions receive 250 to 500 mm (10 to 20 in.) of precipitation each year and have grass or shrub steppe vegetation with patches of unvegetated soil exposed between grass clumps or shrubs. Other factors (geology, topography, and land use) being equal, a semiarid climate results in the greatest sediment yield to channels (Langbein and Schumm 1958; Rogers and Schumm 1991) and high values of drainage density (Schumm and Hadley 1961). Channels in semiarid regions share many of the same characteristics as channels in arid regions (Goudie 2013), including substantial spatial and temporal variability in precipitation, peaked flood hydrographs (Figure 37B), large interannual variability in floods, and channel geometry that changes substantially over a period of several decades (Friedman and Lee 2002; Jaquette et al.

2005). Consequently, semiarid regions, like arid regions, can be particularly challenging environments in which to delineate an OHWM.

4.1.3 Humid temperate regions

Humid temperate regions receive amounts of annual precipitation that exceed annual evapotranspiration. These areas lie between 30° and 60° north latitude and include substantial variability in precipitation amounts and seasonality between discrete portions of this latitude belt (subdivisions include warm continental, hot continental, subtropical, marine, prairie, and Mediterranean). Both polar and tropical air masses can affect humid temperate climates, and seasonality is typically pronounced. Humid temperate areas commonly have continuous vegetation cover of tallgrass prairie or forest, with high infiltration and limited surface runoff during precipitation.

Rivers in humid temperate regions have less flow variability within a year and between years than channels in arid and semiarid regions; channels in humid temperate regions are much less likely to go completely dry, for example. Rivers in humid temperate regions can nonetheless experience large floods caused by convective storms in small watersheds or extensive and prolonged frontal rainfall, snow, or dissipating tropical storms in larger watersheds (Figure 37C). Large floods can create erosion and deposition that obscure the OHWM for a period of a year or more, especially along channel segments where the flood substantially alters the channel and the adjacent floodplain.

4.1.4 Tropical regions

Tropical regions lie between 25° latitude north and south and can be humid tropical or seasonal tropical. Seasonal tropical regions have a pronounced dry season during which the driest month receives less than 60 mm of precipitation. Within the United States, Hawaii and Puerto Rico both have seasonal tropical climates. Rainfall in tropical regions can reach very high intensities; and even where undisturbed rain forest is present, rapid transmission of runoff to channels creates a flashy hydrograph with rapid rise and fall of stream flow and substantial sediment transport (Niedzialek and Ogden 2005; Wohl and Jaeger 2009). Frequent storms and large volumes of rainfall per unit drainage area create an annual hydrograph characterized by numerous, short duration, peaked floods (Figure 31D), resulting in an OHWM that is well above base flow in most channels.

4.1.5 Boreal regions

Boreal regions lie between 50° and 70° north latitude, which limits U.S. boreal regions to Alaska. These regions typically have continuous forest cover at lower elevations and tundra vegetation at high elevations. Boreal areas have long, usually very cold winters and short, cool to mild summers. Annual precipitation is typically less than 380 mm (15 in.). Despite the relatively low precipitation, standing water and perennial rivers are abundant because much of the ground is underlain by continuous or discontinuous permafrost that limits infiltration. Extensive wetlands and floodplains create flood peaks that are of relatively low magnitude and long duration (Figure 37E) so that the OHWM is not as high relative to base flow as in warm, dry regions.

Thick winter ice over rivers in boreal regions creates some unique hydrologic processes and channel features. River ice modifies stream flow by (i) reducing groundwater inflow when anchor ice freezes to the streambed; (ii) storing river water within ice, which typically involves slower removal of river water during freeze-over and rapid release of melting water during breakup in spring; and (iii) increasing the hydraulic resistance to flow because of the ice cover, which has the effect of increasing the water-surface elevation—this can be especially significant during breakup when ice jams form (Prowse and Beltaos 2002; Ettema and Kempema 2012). The frequency of ice jams and the resulting floods are highly variable from year to year (Boucher et al. 2012), but breakup typically creates the annual maximum water levels (Prowse and Carter 2002; Prowse and Ferrick 2002). Ice jams can also cause channel avulsion in which the main channel moves laterally, sometimes over distances several times the width of the active channel. Ice jams, although less common, can also occur on rivers in the northern portions of temperate latitudes.

Boreal rivers draining glaciers commonly have peak flows during mid to late summer when glacial melting is most pronounced (Woo and Thorne 2003). Rivers in this region downstream from large wetlands can also have prominent snowmelt peaks in late spring to early summer (Woo and Thorne 2003).

4.1.6 Arctic regions

Arctic regions lie north of the Arctic Circle at latitude 66°33′ N; U.S. Arctic regions are confined to Alaska. The Alaskan Arctic has cold winters and cool summers but is relatively dry, receiving less than 250 mm (~10 in.) of annual precipitation. The ground is underlain by continuous permafrost, which limits infiltration. This, combined with very low rates of evapotranspiration, supports abundant surface water despite the low precipitation inputs. Arctic regions include forested areas and, at the higher elevations and latitudes, tundra and non-forested wetlands. As in boreal regions, stream flow response to precipitation inputs is muted, but elevated water surfaces can be associated with ice jams (Figure 37F).

4.2 Variations in the OHWM in relation to streamflow regime

Streamflow regime can be described in at least three basic ways (Table 7). The first differentiates rivers based on the consistency of flow, with ephemeral, intermittent, and perennial rivers as defined previously. Ephemeral rivers are dry much of the time because of limited surface runoff, lack of groundwater inputs, and high infiltration rates into the streambed during surface flow. These conditions are characteristic of very dry climates, karst regions with substantial subsurface flow, and very small headwater catchments with minimal contributing drainage area.

Table 7. Characteristics of different streamflow regimes in the United States.

Streamflow Regime	Types of Precipitation	Relative Seasonal Variability	Relative Interannual Variability
Consistency of flow			
Perennial	all	lower	lower
Intermittent	all	moderate	moderate
Ephemeral	all	higher	higher
Dominant source of flow			
Snowmelt	snow	high	lower
Snow-and-rain	snow and different types of rain	moderate	moderate
Rainfall	frontal convective thunderstorms cyclones, hurricanes	high highest high	high highest high
Spring-fed	all	dampened, with peak flow months after precipitation	lowest

Intermittent rivers occur where small springs create surface flow, but evaporation and infiltration into the river bed create too much water loss downstream to sustain year-round surface flow. Intermittent rivers can also form where the channel alternates downstream between relatively impermeable bed materials that correspond to surface flow and permeable bed materials that facilitate infiltration and subsurface flow or where seasonal changes in evapotranspiration or in permeability (e.g., active layer above permafrost) influence water-table elevation (Larned et al. 2010).

Perennial rivers also experience infiltration into the river bed and evaporation from the river flow, but the discharge is sufficient to maintain year-round surface flow. Perennial rivers are typically maintained by groundwater inputs that support base flow. Surface and shallow subsurface runoff from precipitation inputs creates varying amounts of additional flow superimposed on the base flow.

A second basic classification for streamflow regimes focuses on the type of precipitation that causes most of the flow in the river. The four basic categories are snowmelt, snow and rain, rainfall, and springs (Table 7). These categories are not mutually exclusive—a predominantly snowmelt flow regime can also receive rainfall runoff—but instead designate the single most important source of river flow.

Snowmelt flow regimes (Figure 2B) characterize higher latitudes and higher elevations within the United States, where melting of the winter snowpack produces the annual peak flow. Although the volume of water within the snowpack and the rate at which the snow melts vary from year to year, producing interannual variability in the yearly peak flow, this variability is commonly lower than in rainfall-dominated rivers. Rivers in which peak annual discharge occurs primarily in response to snowmelt may be the most likely to follow "expected" relationships in that a morphologically defined bankfull discharge is likely to occur every 1 to 2 years and to transport the majority of sediment (e.g., Torizzo and Pitlick 2004). These are some of the most straightforward rivers in which to delineate the OHWM.

Snow-and-rain flow regimes can refer to rivers with a bimodal peak flow regime, such as in mountainous regions in the western United States that receive an early summer snowmelt peak flow and a late summer convective rainfall peak flow. *Snow-and-rain* can also refer to channels in which rain-on-snow events create the largest peak flows. In either scenario, the snowmelt peak flows are likely to be more consistent in timing and magnitude from year to year than are the rainfall peak flows. The rainfall peak flows are likely to be of higher magnitude and shorter duration than the snowmelt peak flows. The existence of two populations of peak flows on a single channel can result in OHWM indicators occurring at more than one elevation along the channel.

The category of rainfall-dominated stream flow (Figure 2B) includes very different types of rainfall. Convective summer thunderstorms typically cover relatively small spatial areas (20–50 km^2) for short periods of time (generally less than 1 hour) (Barry and Chorley 1987) but can create intense precipitation that leads to rapid surface runoff and flashy peak flows in smaller drainage basins. Cyclonic precipitation occurs when air ascends through horizontal convergence of airstreams in an area of low pressure (Barry and Chorley 1987). Cyclonic precipitation is typically of lower intensity, greater spatial extent, and longer duration than convective precipitation. Cyclonic precipitation can be subdivided into frontal precipitation associated with the movement of a warm or cold front, tropical and subtropical cyclones, hurricanes, and monsoonal depressions.

Mountainous regions can also experience orographic precipitation in which higher-elevation areas trigger convective instability, increase cyclonic precipitation by slowing the rate at which an atmospheric depression is moving, or cause convergence and uplift as valleys funnel airstreams (Barry and Chorley 1987; O'Connor and Costa 2003). Orographic precipitation is essentially an elevation-related enhancement of convective or cyclonic precipitation.

Springs occur where the water table (the upper surface of the groundwater) intersects the ground surface. Springs can be seasonal and cease to flow during the annual dry season or during periods of drought, or springs can be substantial point sources of water that flow year-round even during droughts (Alfaro and Wallace 1994). Seasonal springs typically have smaller discharge and give rise to intermittent river segments (e.g., Scheurer et al. 2003). Perennial springs create perennial rivers, some of which are quite large at the spring-head. Springs are most common where subsurface flow conduits can develop because of dissolution of subsurface materials (e.g., karst springs in limestone bedrock) or because of differences in permeability that concentrate subsurface flow (e.g., springs in layered volcanic rocks of Idaho, Oregon, and Montana, as described in Whiting and Moog [2001] or O'Connor and Grant [2003]).

Another approach to categorizing streamflow regimes focuses specifically on seasonal and interannual variability of base flow and floods. Poff and Ward (1989) and Poff (1996) used long-term discharge records from rivers across the continental United States to distinguish nine river types based on flow regime (Table 8).

Table 8. River types based on flow regime (after Poff and Ward 1989 and Poff 1996).

River type	Description
Harsh intermittent	Long periods of zero flow and very low flow each year; mostly in the arid to semiarid southwestern United States
Intermittent flashy	A high frequency of floods that are moderately seasonal; mostly in the arid southwestern United States
Intermittent runoff	Less frequent and less predictable floods; mostly in the semiarid central United States
Perennial flashy	A high frequency of nonseasonal flooding and surface flow supported by subsurface flow; mostly in the arid to semiarid portions of the United States
Perennial runoff	Less frequent floods and less influence by subsurface flow; mostly in the more vegetated, mesic regions of the United States
Snowmelt rivers	Very predictable floods but do not necessarily flood every year; mostly in western mountains
Snow plus rain	Also in mountains of the western United States but differing from snowmelt streams in their greater flood frequency and lesser flow and flood predictability
Winter rain	Characterized by intermediate flood frequency and moderate to high seasonality of flow and flooding; mostly in the Pacific Northwest
Mesic groundwater	The least flow variability; generally in the eastern United States

Regardless of the streamflow classification that is used, the key relationship between the flow regime and the OHWM is that, other factors being equal, the more variable the flow is, either within a year or between years, the more difficult it becomes to delineate an OHWM. When flow is extremely variable through time, as in intermittent runoff rivers or perennial flashy rivers (Poff 1996), repeated fluctuations in water level can create multiple geomorphic and vegetative indicators. An arid-region ephemeral river, for example, might exhibit instream bedforms such as gravel bars created by ordinary floods and erosional features such as truncation of alluvial fans created by extraordinary floods. If the OHWM identification occurs soon after the extraordinary flood and before ordinary floods create lower-elevation indicators, then designation of the OHWM can be challenging.

4.3 Variations in the OHWM in relation to position in the drainage network and to valley and channel geometry

A useful way to think of relative river size is to use the Strahler (1952) stream-order system. A first-order river is one with no tributaries. A second-order river is present downstream from the junction of two first-order rivers, and two rivers of equal magnitude must join to form the next stream order (Figure 41). This classification depends on the scale and spatial resolution of the map of a drainage network; very small headwater channels, in particular, can be included or excluded on different maps. Increasing stream order implies increases in relative discharge and channel dimensions but does not bear any consistent relation to absolute discharge, channel dimensions, or flow regime because of intersite differences in discharge and channel substrate. For example, downstream hydraulic geometry relations indicate that in many rivers, the channel width increases proportional to the square root of the mean annual discharge (i.e., $w = Q^{0.5}$ [Leopold and Maddock 1953]). However, basin-specific exponents in this equation vary from 0.1 to 0.8 (Park 1977), indicating that, between river networks, width can increase at differing rates downstream as discharge increases. That is, a second-order channel in Oregon's Coastal Range could have very different discharge and channel dimensions than a second-order channel in southern Florida. Even within a river network that has a relationship between channel width and discharge described by the equation of a best-fit line, individual channel cross sections will exhibit scatter about the best-fit line (Figure 42); if width increases proportional to the square root of discharge for the river network as a whole, individual sites within the network might have a width–discharge relationship better characterized by an exponent of 0.2 or 0.6. Increasing stream order does not signify increasing base flow in arid-region ephemeral or intermittent rivers that may lose surface flow downstream as a result of infiltration or evaporation, although peak flow may increase downstream with stream order in these river networks.

Figure 41. Illustration of the Strahler (1952) stream-order system. First-order channels (*blue*) have no tributaries. Second-order channel segments (*maroon*) are formed by the junction of two or more first-order channel segments. Third-order channel segments (*green*) are formed by the junction of two or more second-order channel segments.

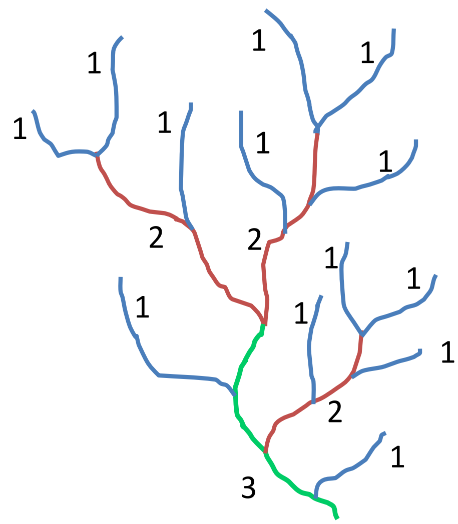
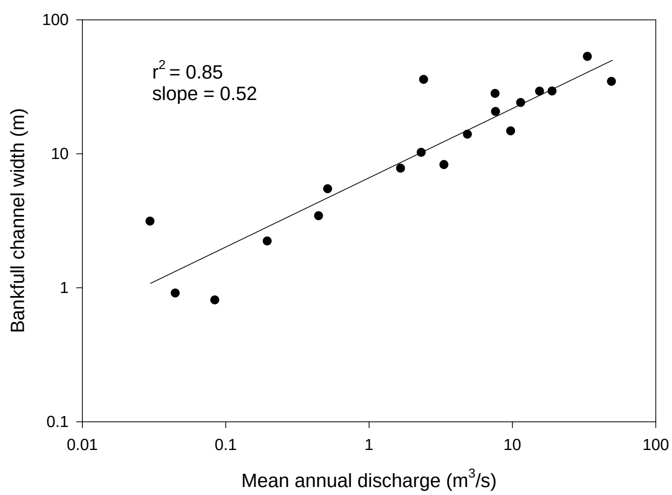


Figure 42. Example of scatter in the relationship between mean annual discharge and bankfull channel width, showing the best-fit line and corresponding equation. These data come from the Chena River in Alaska. The most typical exponent for this relation is 0.5; these data have an exponent of 0.52.



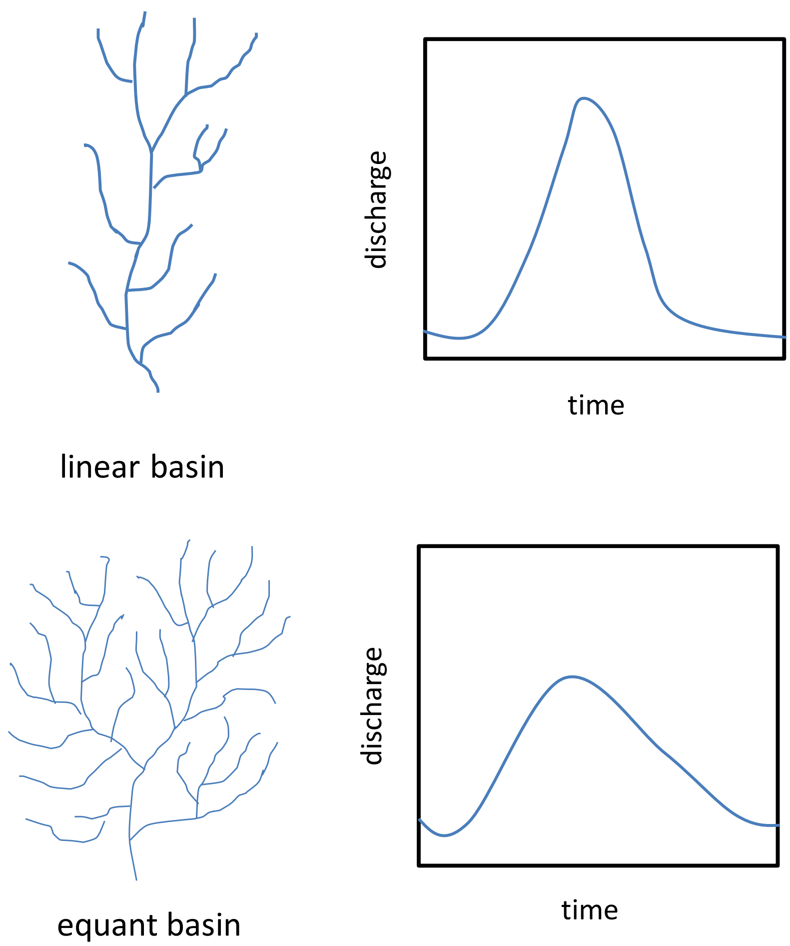
Designating the stream order of a particular channel segment does give a little more information than simply referring to a small river or a large river. Even the term "headwaters," which is widely used, can imply very different sizes of channels or flow regimes, depending on the spatial scale of interpretation. Here, we discuss differences in small or headwater rivers (first to third order), moderate rivers (fourth to sixth order), and large rivers (greater than sixth order).

Small rivers have relatively small drainage areas that can contribute runoff during precipitation, but small rivers also have less floodplain area and volume of subsurface sediments in uplands and river corridors to store runoff. Steeper topography and shallower soils in some small river catchments can also result in rapid downstream transmission of runoff. Small rivers consequently have less ability to attenuate flood peaks, and a characteristic flood hydrograph for a small river is relatively peaked—high in magnitude and short in duration—with a higher maximum discharge per unit drainage area (i.e., $m^3/sec/km^2$). Smaller drainage areas are also more likely to be mostly or completely covered by a storm that produces large amounts of precipitation, such as a summer convective storm, which means that the entire drainage area is contributing runoff to the river. As drainage area increases, a storm is less likely to affect the entire drainage or to affect the entire drainage simultaneously so that some portions of the catchment contribute minimal runoff to the storm hydrograph or contribute runoff to different parts of the hydrograph.

As drainage area and stream order increase, peak discharge is likely to reflect at least two influences beyond precipitation inputs: river network configuration and valley geometry. River network configuration refers to the spatial arrangement of individual channels and their confluences within a network. For a similar precipitation input, a linear configuration reduces travel time to the main channel and results in larger peak discharges that occur rapidly whereas a more equant-shaped basin results in more attenuated floods (Figure 43). Valley geometry influences flood peaks by creating more or less attenuation in surface and subsurface areas. Broad, low-gradient valleys are likely to have extensive floodplains and underlying alluvial aquifers that temporarily store and gradually release flood waters, creating a lower-magnitude but longer-duration flood peak relative to the flood peak produced by narrow, steep valleys.

Based on these trends, the absolute magnitude of bankfull discharge or the ordinary high water level and the duration and recurrence interval of this flow would be expected to increase downstream as drainage area increases; and numerous studies indicate that this is the case (e.g., Petit and Pauquet 1997). The magnitude of discharge that produces the OHWM standardized per unit drainage area ($m^3/sec/km^2$) can be expected to decrease. These relations may not be linear, however, because of abrupt downstream changes in climate (e.g., elevation-related changes in precipitation within mountainous areas), river network configuration, or valley geometry. Consequently, limited site-specific information on the OHWM cannot necessarily be used to extrapolate to other sites even within the same drainage basin, let alone between basins. Field verification of the OHWM at each site of interest remains very important.

Figure 43. Illustration of linear and equant basin shapes and idealized drawings of the associated flood hydrographs.



This last point is also illustrated by the influence of variations in cross-sectional channel geometry on the OHWM. The OHWM can be higher relative to average river-bed elevation at narrow channel cross sections where increasing discharge creates large increases in flow depth, as is commonly the case at channel cross sections where flow gages are located and where bankfull return intervals are estimated. Again, in a regulatory context, the

OHWM cannot necessarily be accurately extrapolated from a few measured sites to other sites within a river network or in other networks. The accuracy of the OHWMs extrapolated from one site to others will depend strongly on the uniformity of the channel geometry and on factors such as drainage area, channel substrate, and channel gradient. Engineered channels are more likely to have a uniform geometry and cross-sectional area downstream. Natural channels are always heterogeneous to some degree, which can limit the accurate extrapolation of the OHWM determinations among sites along the channel.

4.4 Variations in the OHWM in relation to channel substrate

Channel substrate refers to the composition of the river bed and bank materials. In many channels, the bed is of coarser-grained sediment than the banks, although the banks are commonly stratified with coarser material near the base of the bank from channel lag and lateral accretion deposits and finer sediment near the top of the bank produced by overbank, vertical accretion (Figure 44). Channels formed in steep terrain may not have a floodplain and may have banks formed in sediment deposited from adjacent uplands through rock fall, debris flow, slope wash, or other processes.

Basic substrate categories include bedrock, silt and clay, sand, gravel, boulders, and mixed bedrock-alluvial. Bedrock is cohesive, lithified material although bedrock such as shale or weakly consolidated sandstone can be easily eroded by a river. Some bedrock can form under surface or near-surface conditions, such as calcium carbonate deposited in the form of tufa or travertine along a river channel (Fuller et al. 2011). Silt and clay-sized particles (less than 0.06 mm diameter) are also cohesive and display many of the same types of channel geometry as channels cut into bedrock. Sand-sized particles (0.06–2 mm diameter) form the most readily eroded channel substrate because sand grains have relatively low cohesion and relatively little flow energy is required to mobilize and transport sand grains. Other materials (e.g., silt, clay, roots of riparian vegetation, and large wood) typically help to stabilize the banks in sand channels. Gravel-sized particles (2–256 mm) require substantially more flow energy to be mobilized and transported, as do boulder-sized particles (greater than 256 mm diameter). Mixed bedrock-alluvial channels are those with bedrock underlying a relatively thin veneer of bed alluvium and bank deposits. The alluvial deposits may be eroded during a flood, but the underlying bedrock limits widening and deepening of the channel cross section.

Figure 44. Example of stratified stream banks, here along the Aichilik River, Alaska (bank is approximately 2 m tall).

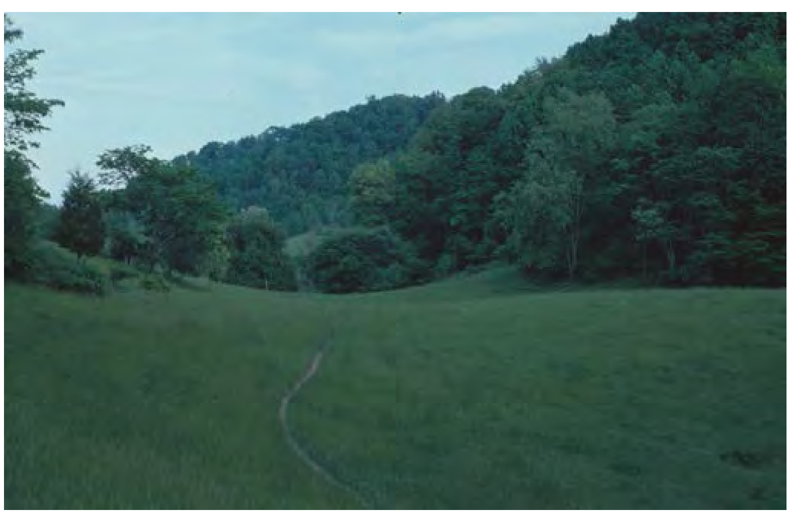
The energy required to mobilize particles in the channel bed and banks becomes important with respect to the OHWM because variations in channel substrate erodibility between sites can create large differences in the OHWM, even if flow magnitude does not vary between the sites. These differences in the OHWM reflect channel cross-sectional stability during the ordinary high water flow. Flow depth will increase rapidly with increasing discharge in erosionally resistant channels until the channel bank is overtopped. In contrast, sand-bed channels commonly experience substantial bed scour during the rising limb of a flood and bed filling during the falling limb so that the OHWM remaining after the flood can be much closer to the river bed than in an erosionally resistant channel; in effect, the channel cross-sectional area enlarges during the flood and then constricts after the flood.

Rivers in karst terrains present a special and sometimes very complicated scenario with respect to the height of ordinary high water (Brahana and Hollyday 1988; Agouridis et al. 2011). Karst terrains occur where soluble bedrock, typically limestone or dolomite, creates underground conduits that can carry substantial volumes of water. Water flowing in a surface channel can abruptly disappear into the subsurface if one of the underground conduits intersects the ground surface, or a substantial surface flow can start at a large spring fed by an underground conduit (Figure 45). The relationship between surface and subsurface flow can also depend on discharge. During base flow, for example, all of the water in a normally dry channel may be contained in an underground conduit, but the conduit may be too small to contain storm runoff, creating surface flow during and immediately after sufficient precipitation. This type of interaction can mean that the only prominent HWM along a surface channel is associated with extraordinary, infrequent high flows (Legrand and Stringfield 1973; Ford and Williams 1989; Campbell 2007).

Figure 45. Examples of channel features in karst terrains. (*A*) A spring emerging from a limestone outcrop at Vasey's Paradise along the Colorado River in Grand Canyon, Arizona. (*B*) A dry valley in southern West Virginia. This area receives an average of 1.25 m (49 in.) of precipitation a year but has no surface drainage along valleys such as this one because of subsurface karst conduits.

A

B



5 Processes and Time Periods of Recovery Following Disturbance

This section reviews factors that influence channel stability, including the time necessary for a channel to return to its pre-flood configuration, and the formation and preservation of HWMs. Influential factors include climate, variability in river flow, erosional resistance of the channel boundaries, condition of the channel at the time of the flood, and position in the drainage network. This section reviews diverse forms of channel change, also. The key point relative to the OHWM is that HWMs are preserved in different manners and for periods of different duration, depending on a variety of channel characteristics and flow history.

5.1 Channel stability and resilience

Rivers commonly have more than one HWM. Different types of geomorphic and vegetative HWMs along the river record differing magnitudes of flood. An extraordinary flood along a confined valley may have left erosional features elevated well above the active-channel boundaries, for example, and influenced the age distribution of woody vegetation whereas lower-elevation HWMs were created by more ordinary floods. The ability to detect any HWM, as well as the relevance of any HWM to the contemporary channel, reflects the influence of climate and channel stability and resilience. Climate is important through its influence on the processes that tend to obliterate HWMs after the flow recedes from that point. Such processes include soil development or rock weathering (Patton 1988; Levish 2002); growth of vegetation (Patton 1988; Dean and Schmidt 2011); surface erosion along the channel from non-fluvial processes such as slope wash (Dezileau et al. 2014); bank sloughing during freeze–thaw (Lawler 1993); or infrequent (extraordinary) high flows that remove erosional, depositional, or vegetative indicators of more frequent (ordinary) high flows (Kochel and Baker 1988). The rate at which these climate-influenced processes can obscure HWMs varies from years for substantial vegetative growth in wet climates (Kite et al. 2002) to decades or centuries for soil development in dry climates (Greenbaum et al. 2000; Webb et al. 2002). Ideally, something that is an *ordinary* HWM is recreated at relatively frequent intervals and thus remains readily visible, but this is not always the case.

Channel stability and resilience are particularly important in the context of extreme high flows that remove the OHWM. As noted earlier, a stable channel can be defined as one with no net change over the time interval being considered. Channel stability thus refers to the ability of a channel to resist changes in cross-sectional geometry, planform, or gradient during a specified time interval or to return to pre-disturbance conditions (Mackin 1948; Nanson and Huang 2008). A stable channel with a resistant boundary experiences relatively little net erosion or deposition during a large flood. A stable alluvial channel can change substantially during a large flood, but subsequent smaller flows can quickly rework the erosional and depositional features created during the large flood, returning the channel to its pre-flood configuration. Resilience describes the tendency of a channel to return to its pre-flood configuration following a large flood (Brunsden and Thornes 1979; Bull 1991; Wohl 2010a). A resilient channel might undergo substantial erosion or deposition during a 50-year flood, for example; but subsequent smaller flows could rework the channel boundaries to pre-flood geometry within 2 or 3 years. In contrast, a channel lacking resiliency might retain some aspects of channel geometry—such as width-to-depth ratio—created during the big flood until the next flood of similar or larger magnitude occurs (Baker 1988; Lang et al. 2013). These concepts are expressed in the characteristic form time for channel geometry (Wohl 2010a). A persistent channel geometry is one that lasts longer than the recurrence interval of the flow that created or modified it. A transient channel geometry is one that has a shorter duration than the recurrence interval of the flow that created it.

Individual portions of a river can vary enormously in their stability and resilience. Channels formed in erosionally resistant materials, such as boulders, cohesive fine sediment, or bedrock, tend to be stable but not resilient; a flow with enough magnitude and energy to change the channel boundaries is likely to leave persistent geometric features (Baker 1988). Steep, narrow valley segments are also more likely to be shaped predominantly by very large floods that generate substantial erosive energy. In wider, lower gradient valley segments, the energy associated with large floods is dissipated in shallow flow across the floodplain; and the channel changes created by large floods are more readily modified by subsequent, ordinary floods (Patton 1988).

Condition of the channel at the time of the flood can also influence stability and resilience. A flood may enhance the trajectory of a river segment that was already incising before the flood, for example, but have less effect on a river segment that was stable. Or a flood may cause greater erosion along a river segment where woody vegetation was recently killed by a fire or removed as part of river management (Griffin et al. 2010).

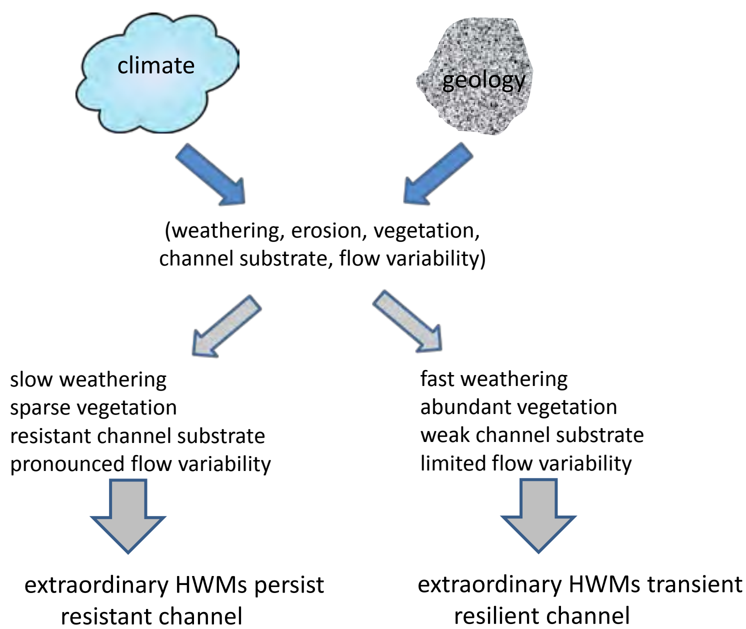
Other factors being equal, rivers with smaller drainage area tend to be less resilient because of lower magnitudes of flow energy during ordinary floods relative to the erosional resistance of the channel boundaries (e.g., Gooderham et al. 2007). Intense precipitation, such as a convective storm of spatially limited extent, can create substantial runoff over the entire drainage basin of a small river, creating high values of discharge per unit drainage area and correspondingly large channel change that subsequent smaller flows cannot modify (Kochel 1988).

Resilience and resistance are also sometimes expressed in terms of equilibrium. A channel in static equilibrium can be resistant and undergo little change during a large flood. A channel in steady-state equilibrium can be resilient, undergoing change during the flood but rapidly returning to pre-flood conditions (Schumm 1977).

The effects of channel-boundary resistance to erosion, drainage area, and valley geometry all interact to influence resilience of channels and floodplains and preservation of the OHWM and extreme HWMs. Also, because flow energy is concentrated within channels and dissipated across floodplains, channels may be more resilient than floodplains (Kite and Linton 1993) (Figure 46).

Channels in climates with greater hydrologic variability tend to be less stable and of limited resilience. An example comes from channels that repeatedly alternate between meandering and braided planforms over a period of many decades. Such scenarios have been described for sand- and gravel-bed channels in seasonally dry regions of western California (Kondolf et al. 2001), western Colorado (Jaquette et al. 2005), eastern Colorado (Friedman and Lee 2002), and southern Arizona (Burkham 1972). An unusually large flood creates a braided-channel planform and removes most of the woody riparian vegetation that helps to stabilize the channel banks. The flood also creates germination sites for new riparian vegetation, however; and woody riparian vegetation gradually regrows during the next few decades if flood peaks remain low to moderate. The vegetation stabilizes the banks and traps sediment, allowing the channel to narrow and gradually become meandering until the next very large flood once again causes substantial erosion and returns the channel to a braided planform.

Figure 46. Schematic illustration of factors that influence the persistence of ordinary and extraordinary high water marks and the resilience or resistance of a river. This illustration focuses on natural factors rather than human effects. Human activities that change characteristics such as land cover, flow variability, and resistance of the channel substrate can strongly influence the persistence of ordinary and extraordinary high water marks, as discussed in chapter 6.



Another category of rivers that are less stable and of limited resilience are steep channels in mountainous portions of any climatic region. Debris flows can periodically occur within these channels. A debris flow is a rapid movement of saturated soil, rock, and water, commonly confined within a channel, that moves as a slurry downslope or downstream from the point of initiation (Ebel et al. 2015). A debris flow can generate enormous force and create erosional and depositional features that subsequent water flows have limited ability to modify (Costa and Jarrett 1981; McCoy 2015). Consequently, the presence and elevation of an OHWM in these channels can be strongly influenced by the time since the last debris flow because that debris flow likely shaped the overall channel geometry (Wohl and Pearthree 1991; Bigelow et al. 2007).

The time for a channel to recover following a disturbance such as an extreme flood or debris flow is defined as the time necessary to reform the channel geometry present prior to the disturbance (Wolman and Gerson 1978). Rivers with large hydrologic variability and strong boundary resistance to erosion typically are dominated by infrequent disturbances (Kochel 1988; Whipple 2004; Wohl 2014b); these events create an active-channel geometry that persists until the next major disturbance. Rivers with large hydrologic variability and limited boundary resistance to erosion likely experience major changes in the geometry of the active channel during infrequent or extraordinary disturbances but then gradually return to pre-disturbance channel geometry. In these channels, the delineation of the active channel and the OHWM will be strongly influenced by time since the last major or extraordinary disturbance. Rivers with limited hydrologic variability and limited boundary resistance to erosion are more similar to the first scenario (large hydrologic variability and high boundary resistance) in that they experience less change in active-channel geometry and elevation of the OHWM through time (Figure 46). Because of continuing change in precipitation patterns and land use, however, a recovering channel may stabilize in a new condition rather than returning to conditions present prior to a disturbance.

5.2 Forms of channel change

Channels can change through time in response to several influences, including changes in water and sediment entering the river from adjacent uplands; changes in the resistance of the channel boundaries, especially the banks, to river erosion; and changes in relative base level. This section briefly reviews how channels can adjust in response to altered inputs, boundary resistance, and base level.

Water and sediment yields to channels are the primary drivers of channel form and process, and geomorphologists have developed numerous conceptual models to describe how channels respond to changes in the relative supply of water and sediment. One of the earliest and most intuitive is Lane’s balance, which depicts how channels can respond to increasing the relative supply of either water or sediment (Figure 47) (Lane 1955; Dust and Wohl 2012). The challenge of conceptualizing channel adjustment is that any particular channel segment can respond differently to a change in water or sediment, depending partly on the rate and magnitude of the change in inputs and partly on the state of the channel at the time of the change in inputs. An eroding channel that receives increased sediment, for example, may stop eroding. A stable, straight, gravel-bed channel that receives increased sediment may accumulate sediment on the channel bed, preferentially filling pools or accumulating finer sediment in gravel riffles; or the channel may develop alternate bars or even become braided (Figure 48). A straight channel that is already aggrading may avulse across the valley bottom or become braided.

Figure 47. Original (*upper*) and revised (*lower*) versions of Lane's balance. The revised version recognizes additional forms of channel adjustment in response to altered inputs of water and sediment (after Dust and Wohl 2012, Figs. 1 and 9).

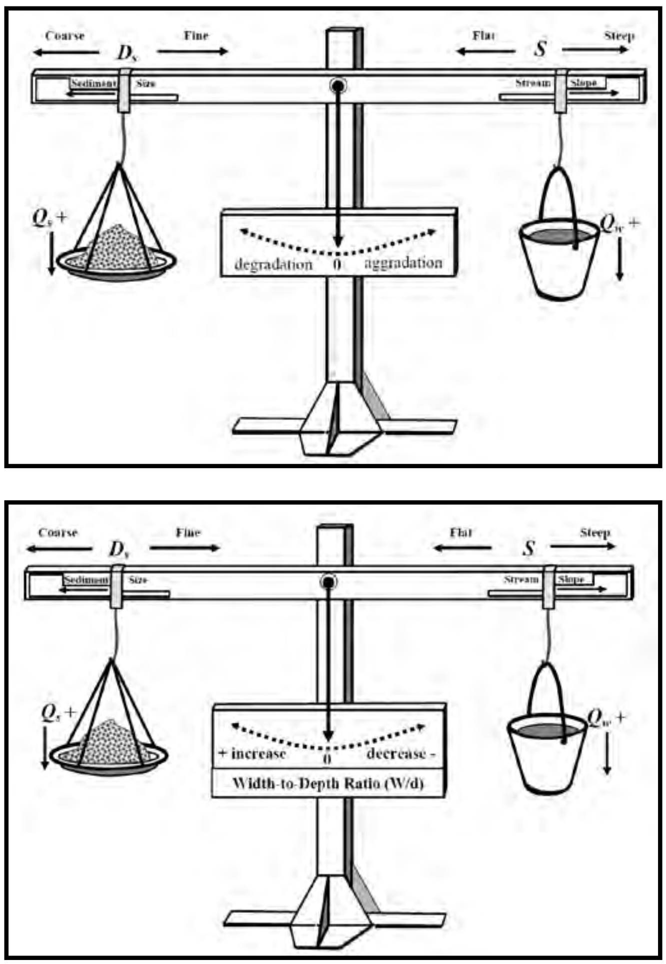
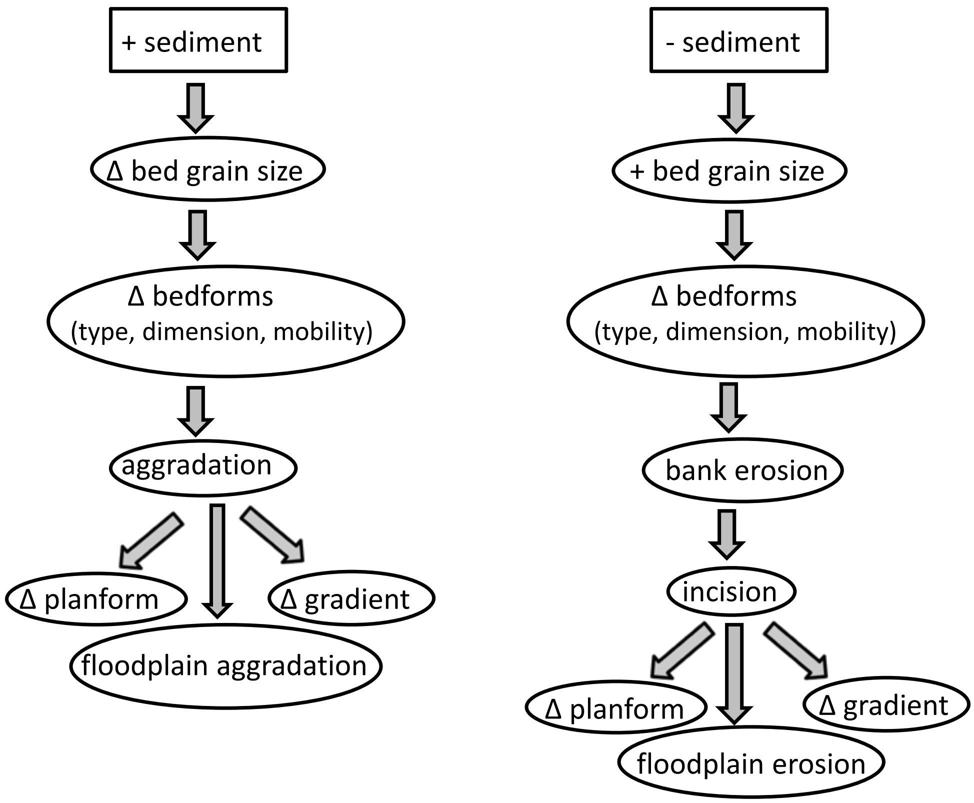


Figure 48. Schematic of the diversity of potential channel adjustments following an increase (*left*) or decrease (*right*) in sediment inputs to a river.

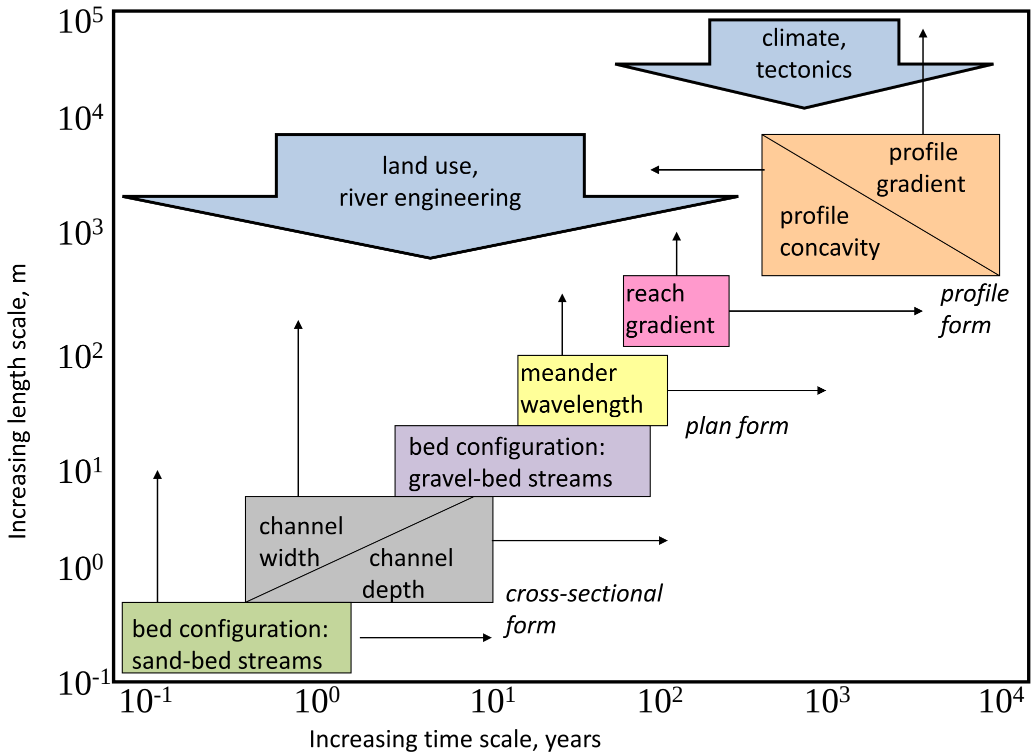


The erosional resistance of a channel's bed and banks can change in response to altered land use in the riparian corridor, altered riparian vegetation, and river engineering. Land uses such as cropping and grazing typically reduce the soil moisture and cohesion of river banks and also remove native vegetation that helps to stabilize the banks (e.g., Trimble and Mendel 1995). Changing the type of riparian vegetation (e.g., replacing trees with grass) or the species (e.g., exotic species displacing native species) can alter the above-ground density of vegetation and the root structure within the banks, thus altering the hydraulic forces exerted against the channel banks and the erosional resistance associated with plant roots (Pollen and Simon 2005; Pollen-Bankhead and Simon 2010; Polvi et al. 2014). River engineering, such as bank stabilization, dredging, and channelization, can alter channel geometry and thus the hydraulic forces exerted against the channel bed and banks and the ability of the channel boundaries to resist these forces (Kesel and Yodis 1992; Simon et al. 1999).

Base level is the lowest elevation to which a river erodes. A large river forms a local base level for each tributary entering the larger river. A particularly resistant point along a river's course, such as a bedrock ledge or a stabilized bridge crossing or grade-control structure, can also form a local base level that limits downcutting by upstream portions of the river network. Sea level forms the ultimate base level for any river that flows to the coast. If the drainage basin is uplifted by tectonic forces, or the base level drops (e.g., by eroding through a bedrock outcrop or destroying a grade-control structure), the downstream gradient of the river becomes steeper. Stream power is the product of discharge and gradient, so a steeper river has more energy to transport sediment and erode the channel boundaries (Wohl 2014c). Conversely, if base level rises—because of aggradation in a larger river, rising sea level, or subsidence of the drainage basin—the downstream gradient of the river decreases; and sediment is likely to accumulate along the channel, especially immediately upstream from the rising base level.

Figure 49 provides a conceptualization of the relative time spans and spatial scales of channel response to differing changes in water and sediment inputs, boundary resistance, or base level. Relatively minor changes will trigger adjustments in readily mobile bedforms, such as sand ripples and dunes, and changes in cross-sectional geometry. Larger or more prolonged changes will affect more resistant bedforms, such as cobble-bed riffles or steps, as well as reach-scale gradient, and so on (Figure 49). Most river engineering and most of the changes that might affect the OHWM will occur over intermediate time (years to decades) and space (lengths of tens to thousands of meters) scales.

Figure 49. Schematic illustration of the different time and space scales over which channel geometry adjusts to changes in water and sediment inputs, boundary erosional resistance, or base level (after Knighton 1998, Fig. 5.3).



6 Human-Induced Alterations That Can Affect the OHWM

Diverse human activities that occur directly within a channel or floodplain or within the drainage basin of the channel can alter every factor that influences the OHWM. People can alter the quantity and timing of water and sediment supplied to the channel from uplands or moving down the channel from upstream segments and thus change the magnitude and frequency of flow that constitutes ordinary high water. People can also alter channel geometry and the stability and resilience of the channel. And people can alter the persistence of OHWMs. This section reviews four basic categories of human activities that can affect the OHWM: flow regulation and changes in land cover, channel geometry, and riparian vegetation. Although each category of activity is treated in isolation, many rivers have experienced or continue to experience numerous, simultaneous human-induced alterations that affect the OHWM. As noted earlier, these interacting human-induced alterations can contribute to nonstationarity in the hydrologic record.

6.1 Flow regulation

Flow regulation refers to dams and diversions that change the characteristics of water and sediment fluxes within a channel. The details of these changes vary greatly between specific channels (Table 9). Depending on how a dam is operated, it can change the magnitude, timing, duration, and rate of rise and fall of either peak flows or base flow (Poff and Hart 2002). A dam that stores waters diverted from another catchment can release substantially larger peak flows to downstream portions of a river network (e.g., Wohl and Dust 2012). In general, however, dams typically reduce the magnitude and duration of peak flows (Williams and Wolman 1985; Hirsch et al. 1990), with the net effect of homogenizing flow regimes across distinct hydroclimatic regions, between seasons, and between years (Poff et al. 2007). Homogenization of flow regimes can facilitate channel change and reduce habitat diversity by limiting the periodic erosion and deposition associated with high flows (Rathburn et al. 2009) and allowing woody riparian vegetation to encroach to the edges of a channel defined by base flow (Nadler and Schumm 1981; Johnson 1994). Homogenization of flow regimes can also limit processes on which aquatic and riparian organisms depend (Lytle and Poff 2004), such as thermal cues for fish spawning

(Shuter et al. 2012) or dispersal of plant propagules during peak flow (Nilsson and Svedmark 2002).

Table 9. Influences of flow regulation on water and sediment fluxes.

Type of Flow Regulation	Effect on Water Fluxes	Effect on Sediment Fluxes	Sample References
Dam			
Run-of-river	Has a minimal effect on peak flow and can reduce base flows	Traps all bedload and some of the suspended load	Poff and Hart (2002)
Water storage	Changes magnitude and timing of base and peak flows	Traps all bedload and most or all of the suspended load	Williams and Wolman (1985)
Flood control	Reduces magnitude of peak flows and can change magnitude and timing of base flows	Traps all bedload and most or all of the suspended load	Magilligan and Nislow (2001)
Hydroelectric	Reduces peak flows, increases base flows, and introduces frequent and rapid fluctuations in discharge	Traps all bedload and most or all of the suspended load	Collier et al. (1997) Magilligan and Nislow (2001)
Milldam	Has a minimal effect on peak flow and can reduce base flows	Reduces downstream sediment flux while a dam is present; increases downstream flux once a dam is no longer active and stored sediment erodes	Walter and Merritts (2008) Pizzuto and O'Neal (2009)
Diversion			
Flow extraction	Reduces flows by varying amounts	Reduces sediment transport capacity	Ryan (1997)
Flow augmentation	Increases flows by varying amounts	Increases sediment transport capacity	Wohl and Dust (2012) David et al. (2009)

Flow regulation can also result in changed channel dimensions because of altered sediment supply and sediment transport capacity. Most dams trap the great majority of sediment entering the reservoir upstream from the dam, which commonly results in reduced floodplain sedimentation (Renshaw et al. 2014) and accelerated channel erosion downstream. This erosion can result in bed coarsening, channel widening, and bed incision, depending on the magnitude of disruption of downstream sediment fluxes and the erosional resistance of the channel boundaries downstream from the dam (Phillips et al. 2005; Hupp et al. 2009). If the dam sufficiently reduces peak flows and associated flow energy, downstream portions of a river can also narrow, despite reduced sediment supply from upstream (Grams and Schmidt 2002), particularly if tributaries downstream from the dam continue to introduce substantial volumes of sediment (Curtis et al. 2010; Sabo et al. 2012).

Several quantitative metrics and software routines have been developed that facilitate determination of how much a hydrograph downstream from a dam has been altered from unimpounded conditions (e.g., Richter et al. 1996, 2012; Schmidt and Wilcock 2008; Gao et al. 2009; Sanderson et al. 2012). Assessments of the hydrologic effects of dams can also be complicated by the existence of numerous dams either along a single channel or within a watershed (e.g., Skalak et al. 2013). Legal arguments centered on channels with flow regulation typically focus on whether the flow regulation raises water levels above the OHWM (e.g., Atkinson v. United States 1946[*]). In this context, it is vital to realize that only an estimated 2% of the total length of rivers in the United States are not affected by dams, with most of these rivers being in Alaska (Graf 2001).

Diversions involve moving surface water between individual channels. Flow in the source channel is decreased to some extent, and flow in the receiving channel is augmented. Some flow diversions remove all water from the source channel whereas others remove only a portion of the annual peak flow. Regardless of the proportion of water removed, water withdrawals can cause channel narrowing, accumulation of sediment on the streambed, and a decrease in bed grain size although the type and magnitude of channel response depend on the details of both the flow diversion and the channel (Williams 1978b; Nadler and Schumm 1981; Ryan 1997). Water withdrawal can also result in encroachment of riparian vegetation and replacement of riparian vegetation with xeric, upland vegetation species (Caskey et al. 2015). Withdrawal of groundwater can drop alluvial or regional water tables, causing drying of springs and rivers (Falke et al. 2010, 2011; Kustu et al. 2010). Augmented flow can cause erosion of the channel boundaries, analogous to the changes documented downstream from dams, because of greater flow energy and sediment transport capacity (Wohl and Dust 2012).

In summary, because of the potential for changes in flow magnitude, frequency, and channel dimensions, diverse forms of flow regulation can alter

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[*] Atkinson v. United States (Federal liability for dam backwater). 1946.68 F SUPP 99–103 (D MINN 1946).

the magnitude and recurrence interval of ordinary high water and the type and elevation of OHWMs.

6.2 Changes in land cover

Numerous human activities can change land cover and hence the characteristics of water and sediment entering a channel network from the drainage basin and influencing channel geometry and spatial boundaries of river flow. This section briefly reviews the three basic categories of agriculture (primarily crops but also upland grazing), urbanization, and deforestation and afforestation.

Agriculture can influence runoff from a watershed by decreasing infiltration and the timing and magnitude of evapotranspiration as a result of changes in land cover and wetland drainage, particularly drainage of floodplain wetlands. The best-documented effects of agriculture, however, involve sediment yields. Agriculture typically increases sediment yield when (i) native vegetation is removed for the initiation of agriculture (Knox 1987), (ii) the spatial extent of agriculture within the watershed increases, or (iii) the type of agriculture (crops being grown or technology used to plant fields) changes (De Boer 1997). Increased sediment yield to channels can cause changes in active-channel geometry and conveyance, and hence in the elevation of the OHWM if, for example, the frequency of overbank flow increases (Clark and Wilcock 2000). These effects can extend well downstream into nearshore areas (Gottschalk 1945), making it important to consider changes in agriculture occurring upstream of a particular channel segment. Conversely, reduction in the spatial coverage of agriculture or implementation of soil conservation practices can decrease flood peaks and volumes (Potter 1991; Kuhnle et al. 1996).

The early stages of urbanization can cause substantial increases in sediment yield as land cover and topography are altered, but the primary effects of urbanization are increased water yield to channels as a result of increased impervious surface and stormwater drainage systems (Wolman 1967; Gurnell et al. 2007). Urbanization is also typically accompanied by widespread river engineering that changes network and channel characteristics (Gurnell et al. 2007) in a manner that can lower or raise the level of the OHWM (Annable et al. 2011). The changes in discharge associated with increasing impervious area are highly variable and dependent on watershed-specific conditions (Bledsoe and Watson 2001), but a common scenario is increased magnitude of frequent high flows (Konrad et al.

2005) that creates bank erosion (Wolman 1967; Trimble 1997; Grable and Harden 2006) and causes channels to become wider and straighter (Pizzuto et al. 2000; Galster et al. 2008; Hawley and Bledsoe 2013). Wastewater return flow to channels can also transform channels in arid regions from ephemeral to perennial and enhance growth of riparian vegetation and associated channel narrowing (Hassan and Egozi 2001). Increased evapotranspiration and decreased infiltration can also cause a decrease in total runoff during dry periods (Ferguson and Suckling 1990).

Deforestation can substantially increase water yields from uplands for decades after timber harvest, depending on whether and at what rate the trees regrow, the methods used in timber harvest, and the intensity and extent of forest removal (Whitaker et al. 2002; Schnorbus and Alila 2004; Tonina et al. 2008). Water yield increases partly because of tree removal and partly because of factors such as compaction of soil and construction of roads in association with timber harvest (Wemple et al. 1996; Magilligan and Stamp 1997; Jones et al. 2000).

Deforestation typically has a stronger influence on sediment yield than on water yield. Removal of trees commonly causes substantial increases in sediment yield over approximately a decade although details vary with the intensity and spatial extent of deforestation, the methods used to cut and remove trees, and the topography and climate of the site (Douglas et al. 1999; Constantine et al. 2005). Sediment yield increases because soils exposed during tree removal become more susceptible to surface erosion; compaction reduces infiltration and promotes overland flow, gullying, and shallow landslides; and reduced interception and evapotranspiration increase soil moisture and decrease slope stability (Megahan and Kidd 1972; Megahan and Bohn 1989; Wolter et al. 2010). Roads built in association with timber harvest are commonly the primary source of excess sediment (Larsen and Parks 1997; Jones et al. 2000; Wemple et al. 2001) even after hillslope vegetation has regrown.

Afforestation typically reverses the effects associated with removal of forest cover. Runoff decreases, infiltration increases, peak stream flow decreases, and sediment yields decline (Vanacker et al. 2007; Stewart and Fahey 2010; Tang et al. 2011) although sediment remobilization from hillslope storage sites can cause the effects of deforestation to persist for many decades (Larsen and Román 2001).

In the context of the active channel and the OHWM, the net effect of changes in land cover is to alter water and sediment yield to rivers. As the balance of water and sediment entering the channel changes, channel geometry and associated elevation of the OHWM relative to the streambed are also likely to change. An important consideration here is that these effects can persist for decades to centuries after the land cover change because rivers do not necessarily adjust immediately to changes in water and sediment inputs nor do the adjustments necessarily occur in a linear and predictable manner (e.g., Bartley and Rutherfurd 2005).

6.3 Changes in channel geometry

Human-induced alterations of channel cross-sectional and planform geometry create some of the most substantial changes in channel dimensions and the distribution of the flood waters that create the OHWM. The most important categories of changes in channel geometry are channelization, obliteration of channels, alluvial mining, construction of levees, relocation of channels, and construction of detention ponds for storm waters and retention basins for sediment (Table 10).

Channelization here refers to any activity designed to enhance the conveyance of water downstream within the active channel. Such activities include

- dredging the channel bed;
- stabilizing the channel banks;
- straightening sinuous channels and blocking off or removing channel-margin irregularities, such as embayments; and
- removing naturally occurring obstructions within the channel, such as downed wood or beaver dams.

Table 10. Summary of potential changes in the OHWM resulting from diverse changes in channel geometry.

Change in channel geometry	Potential effects on the OHWM	References
Channelization	Increased channel conveyance lowers the level of the OHWM relative to base flow. This is associated with channel erosion within the channelized reach and sediment deposition downstream.	Harvey et al. (1983) Simon and Rinaldi (2006, 2013)
Obliteration of channels	Superimposing a land use such as crops or urban areas on a former channel typically leads to sheetflooding and greater cross-sectional width between OHWMs; burial of a channel underground removes OHWMs.	Elmore and Kaushal (2008)
Alluvial mining	Aggregate mining can initiate a headcut that moves upstream and can exacerbate downstream erosion. Placer mining can cause channel erosion at the mining site and sediment deposition downstream. Channel erosion will lower the absolute elevation of the OHWM; sediment deposition will likely cause the OHWM on each side of the channel to be farther apart or higher in absolute elevation.	Graf (1979) James (1991, 1993) Gilvear et al. (1995)
Construction of artificial levees	Levees prevent or limit overbank flow and increase the height of the OHWM relative to base flow.	Kesel (2003) Blanton and Marcus (2009)
Relocation of channels	An artificial channel may have a more uniform channel geometry, resulting in greater velocity and lower OHWMs than in otherwise comparable natural channels within the region. An artificial channel may be hydrologically disconnected from floodplain areas, increasing the elevation of OHWMs relative to base flow.	Hegberg et al. (2010)
Construction of detention ponds for storm waters	Detention ponds can attenuate flood peaks, resulting in a lower elevation for the OHWM relative to base flow.	Person et al. (1936) Schoof et al. (1978) Smith et al. (2002)
Construction of retention basins for sediment	Retention of sediment can create downstream sediment deficits, resulting in erosion of the channel bed and banks and a lower absolute elevation of the OHWM	Wyżga (1991) Lenzi (2002) Bombino et al. (2009)

Small-scale channelization activities were undertaken historically to limit overbank flooding, improve navigation, and clear channels for floating of cut logs downstream to saw mills. The Federal Government and state governments undertook channelization starting early in the nineteenth century, and these activities continue at present (Wohl 2014a). More than 340,000 km of rivers were channelized during the first 150 years of European settlement in the United States (Schoof 1980); and rivers as diverse as prairie channels in Illinois (Mattingly et al. 1993) and lowland, sand-bed channels in Tennessee (Simon 1994) were channelized. The net effect of channelization is to increase channel cross-sectional area, reduce hydraulic resistance, increase downstream conveyance and average flow velocity, and therefore decrease the level of the OHWM relative to base flow. Channelization that involves increasing the erosional resistance of the bed and banks can create a more stable active-channel geometry, but simply dredging the bed, straightening the channel, or removing instream wood—without associated bed and bank stabilization—typically increases flow velocity and erosional energy and results in additional changes and instability in the active channel (Harvey et al. 1983; Simon and Rinaldi 2006, 2013).

Obliteration of channels describes any activity designed to remove any surface expression of channelized flow. This can include plowing across very small channels in agricultural areas and burying channels in underground pipes within urban areas or along transportation corridors (Elmore and Kaushal 2008). Attempting to obliterate a channel with an activity such as plowing is likely to lead to sheetflooding and a broader active channel. Burial of a river over substantial portions of the channel's length effectively removes the active channel and the OHWM. Burial over relatively short lengths, as in culverts, typically has only local effects on the OHWM (USACE 2007). The Corps and the EPA note that a break in the OHWM by itself is insufficient to jurisdictionally isolate the upstream water course (USACE 2007).

Alluvial mining refers to extraction of materials from the river bed, banks, and floodplain. Within much of the United States, channels and floodplains are primarily mined for construction aggregate; but precious metals disseminated within river sediments are placer mined in some regions, such as in Alaska (Madison 1981; LaPerriere et al. 1985). Placer mining was historically much more widespread in regions such as the Appalachians (Lecce et al. 2011), California (James 1994), and Colorado and other portions of the Intermountain West (Hite and Waring 1935; Ramp 1960; Hilmes and Wohl 1995).

The headwall of the excavation pit created during aggregate mining can initiate a headcut that migrates upstream, lowering the elevation of the river bed (Sandecki 1989; Kondolf 1994, 1997; Wishart et al. 2008). The excavation can also trap and store much or all of the sediment coming downstream, creating a sediment deficit downstream from the excavation (Chang 1987) and leading to bed and bank erosion. Aggregate mining on floodplains can cause the excavation pit to capture the river, enhancing channel avulsion and triggering channel incision that limits overbank flows (Norman et al. 1998; Rasmussen and Mossa 2011).

Numerous case studies document large increases in local sediment mobility and downstream sediment supply when the coarse surface layer commonly present in gravel-bed rivers is disrupted by placer mining (Van Nieuwenhuyse and LaPerriere 1986; James 1991; Hilmes and Wohl 1995). In some cases, the sediment mobilized by placer and aggregate mining is primarily finer, subsurface material that is carried in suspension and widely dispersed along the downstream river corridor (LaPerriere et al. 1985; Van Haveren 1991). Along other rivers, bedload transport also increases (James 1991). The increase in sediment supply to downstream portions of a channel network is typically so substantial that channel cross-sectional area is reduced through sediment accumulation within the channel, leading to enhanced overbank flows during ordinary high water or leading to complete transformation of straight or meandering channels to braided channels. Placer mining can also cause channel incision where the river is channelized during mining (Gilvear et al. 1995) or other changes in channel configuration and hydraulic resistance (Graf 1979). The effects of historical placer mining can continue to alter rivers for more than a century after mining ceases (James 1993).

Built along or close to the active channel, levees are embankments that are designed to limit the extent of flood waters. Levees can be designed primarily to protect infrastructure, such as transportation corridors (Blanton and Marcus 2009); to enhance downstream flood conveyance by blocking off side channels and floodplain wetlands; or to enhance navigation by maintaining water depths during low flow. Human-constructed levees date at least as far back as the early eighteenth century in the United States

(NHRAIC 1992) and now extend along tens of thousands of river kilometers in the country. Construction of levees is labor-intensive and expensive, so maintenance of levees commonly also involves bank stabilization that reduces lateral channel mobility and thus lateral accretion of floodplains (Kesel 2003). By preventing or limiting overbank flow across the floodplain and into secondary channels, levees effectively increase the height of the OHWM relative to base flow.

Relocation of channels refers to a situation where a portion of the channel, typically a length that is equivalent to at least several times the active-channel width, is physically moved to another portion of the valley bottom. Although this has been done historically for very large rivers (for example, the main channel of Japan's Tone River was diverted more than 100 km to the east starting in 1590 AD (Uzuka and Tomita 1993), most such relocations involve relatively small rivers that are moved to make way for transportation corridors or other land uses, such as croplands or housing (Hegberg et al. 2010). On the one hand, the constructed channel that is built to replace the natural channel commonly has more uniform channel geometry and much less physical complexity than the natural channel, which can result in greater velocity and lower HWMs for a particular flood magnitude than are likely to occur in otherwise comparable natural channels within the region. On the other hand, the dislocated channel may be hydrologically disconnected from floodplain areas and have no overbank flows so that even ordinary floods create relatively high-elevation HWMs within the active channel.

Detention ponds created via a small earthen dam across a channel are small water bodies loosely defined as having a surface area less than approximately 10^4 m^2 (Smith et al. 2002). Detention ponds can also influence the spatial and temporal distribution of flood waters and thus the OHWM. As of 2002, at least 2.6 million small, artificial water bodies existed in the conterminous United States, mostly in the eastern half of the country (Smith et al. 2002). These water bodies can locally increase evaporation, divert and delay downstream water flow, and alter surface water–groundwater interactions (Person et al. 1936; Schoof et al. 1978; Smith et al. 2002).

Retention ponds or detention basins for sediment can be built within the active channel or off channel. Basins within the active channel can be designed to trap all incoming sediment transported in contact with the river bed or only the coarsest grain-size fraction of the bed-material load. Commonly, these basins, which are also known as check dams or sabo dams, are designed to limit downstream sediment transport during debris flows or flash floods. One effect of sediment detention is to increase the erosive energy of river flow downstream from the sediment detention basin, which can lead to erosion of the river bed and banks (Wyżga 1991). Off-channel sediment retention ponds are commonly built to retain suspended sediment and contaminants traveling adsorbed to the sediment; some of these ponds take the form of constructed wetlands. Off-channel sediment retention ponds are less likely than detention basins within the active channel to cause sediment deficits downstream. Any disruption of sediment supply to downstream river segments, however, has the potential to alter the balance between flow energy available for sediment transport and supply of sediment, which can result in erosion of the channel boundaries (Wohl et al. 2015).

The details of how human-induced alterations influence channel geometry and the elevation, type, and preservation of the OHWM vary widely among specific scenarios. Table 10 provides a summary of these details.

6.4 Changes in riparian vegetation

Riparian vegetation strongly influences hydraulic resistance to flow and flow depth (Griffin et al. 2005), erosional resistance of channel banks and overbank areas (Tal and Paola 2007), and channel geometry (Graf 1978; Friedman et al. 1996; Scott et al. 1996; Merritt 2013). Consequently, changes in riparian vegetation can influence the conveyance of the active channel and floodplain and the elevation of the OHWM. Some of these effects may be scale dependent; channel width is more likely to be strongly influenced by riparian vegetation in smaller watersheds, for example (Anderson et al. 2004).

Diverse characteristics of riparian vegetation are important in the context of the OHWM: the type of vegetation (trees, woody shrubs, grasses, and so forth), the spatial extent of vegetation across the valley bottom, the spatial density of vegetation along the channel and across the floodplain, and whether the vegetation is native or introduced. The type and spatial density of vegetation influence how much hydraulic resistance the vegetation creates and over what range of flows (Thorne 1990; Micheli and Kirchner 2002; Pollen and Simon 2005; Pollen-Bankhead and Simon 2010). Plants with flexible stems can create less resistance than rigid tree trunks, for example, but even flexible plants can create substantial resistance if they grow at high spatial densities (Nepf 2012). The spatial extent of plants governs what portions of the active channel and floodplain have enhanced hydraulic resistance and substrate cohesion from plant roots.

The distinction between native and introduced vegetation can be important because some introduced species can grow in extremely dense stands that strongly influence river processes and form. Introduced woody riparian species such as tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) are now widespread throughout the western United States in particular (Friedman et al. 2005). Although the hydrologic effects of species such as tamarisk (i.e., enhanced subsurface water uptake and transpiration) appear to have been exaggerated, there are situations where expansion of introduced plant species can significantly alter ecohydrologic processes such as the elevation of the water table and rates of transpiration (Hultine and Bush 2011), leading to a decrease in stream flow. This is probably more likely to affect base flow than ordinary high water, however. A more direct effect is that removal of introduced species, like removal of native riparian plants, can so destabilize stream banks that it leads to significant channel erosion (Vincent et al. 2008).

Numerous practices result in substantial or complete removal of riparian vegetation, including timber harvest, development of croplands, and urbanization within the floodplain. Riparian grazing can also remove or alter riparian vegetation, especially woody riparian species such as willows (*Salix* spp.). Intensive riparian grazing by domestic or wild ungulates (Beschta and Ripple 2006) typically causes increased bank erosion and sedimentation within the active channel, creating a wider, shallower cross section and enhanced overbank flow (Trimble and Mendel 1995). Reduction in grazing pressure can reduce these effects (Myers and Swanson 1996; Magilligan and McDowell 1997).

6.5 Additional considerations

Diverse human activities affect water and sediment yield to channels and the shape and stability of the active channel and overbank areas. Depending on the specific historical or contemporary human activities present within a drainage basin, the active channel can expand or shrink, and the OHWM can become higher or lower relative to natural conditions. The key points here are to recognize that (i) nearly all rivers within the United

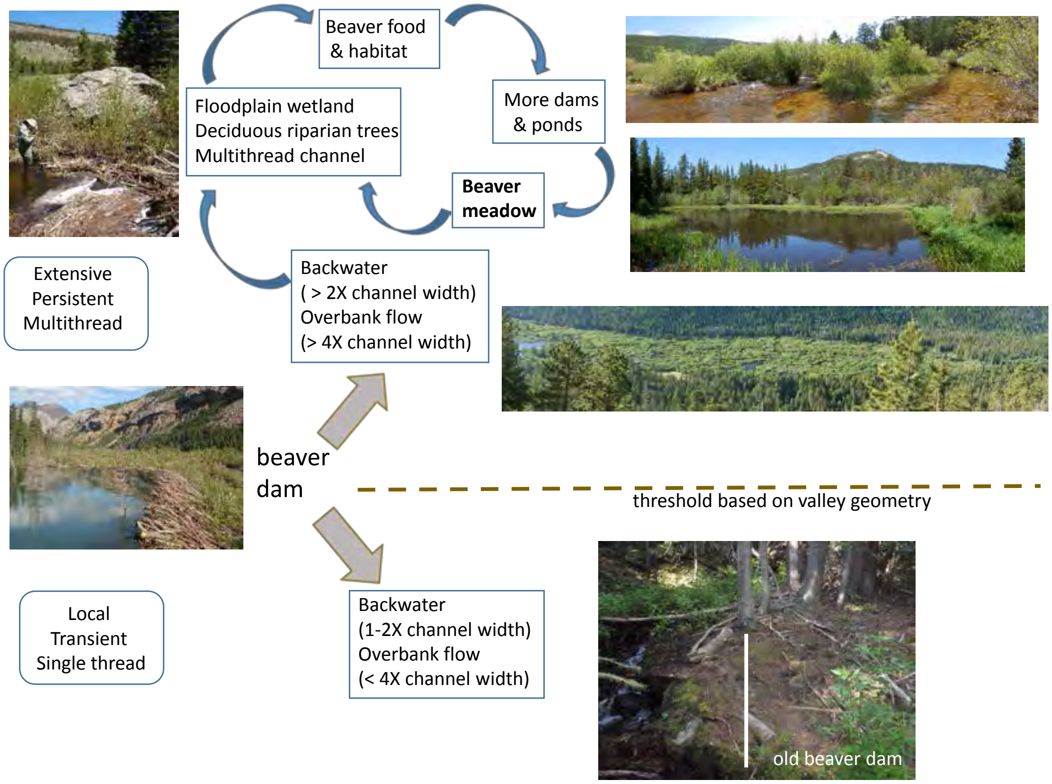
States have experienced some form of historical or human-induced alteration affecting the shape and stability of the active channel and the elevation of the OHWM and (ii) adjustment of the active channel to human activities can occur over many decades and consequently can continue to occur long after the human activities have ceased.

A classic example of persistent human-induced alteration comes from relatively recent work on abandoned milldams in the eastern United States. Walter and Merritts (2008) demonstrated that thousands of milldams were built along rivers in the Mid-Atlantic region during the seventeenth, eighteenth, and nineteenth centuries. Although now abandoned and largely forgotten, these milldams continue to strongly influence channels in the region. While the milldams were intact, each dam accumulated a thick deposit of sand-sized and finer sediment upstream. Now that the dams are abandoned and breached, rivers are incising into these sediment deposits and gradually widening their banks where they flow through the millpond sediment. The characteristic active-channel form in the region is now a deeply incised channel with a gravel bed and tall, nearly vertical, eroding banks of fine-grained sediment. Erosion of the millpond sediment constitutes the dominant source of fine-grained sediment and nutrients to Chesapeake Bay, a nearshore area with severe sedimentation and eutrophication problems. The shape of the active channel and elevation of the OHWM also vary substantially along these channels, depending on how deeply the channel has incised into the old millpond sediment and how rapidly the banks continue to erode. Prior to the work of Walter and Merritts (2008), most scientists and resource managers in the region were unaware of the existence or effect of the milldams. Before construction of the milldams, many of the rivers that are now deeply incised single channels were relatively shallow, multi-channel wetland systems. The historical presence of the milldams thoroughly altered the active channels and the OHWM in these rivers in a manner that persists more than a century after most of the milldams were abandoned. At present, a lively debate continues regarding how to manage and restore these rivers, with advocates of at least two very different scenarios: (i) maintaining deeply incised channels and second-growth riparian forests or (ii) restoring broad, shallow swales with multiple subparallel channels and predominantly marsh vegetation (Marris 2008; Walter and Merritts 2008). The likely continued existence of each type of channel in the Mid-Atlantic Piedmont region implies that the OHWMs will be of different types and at different elevations relative to the active channel in each scenario.

The milldam example illustrates the concept of alternative stable states, an idea originally developed by ecologists (Beisner et al. 2003) that has subsequently been applied to understanding the physical configuration of river ecosystems (Collins et al. 2012; Polvi and Wohl 2013; Wohl and Beckman 2014). Alternative stable states refer to different, equally stable and persistent configurations of a river and floodplain system. Some type of perturbation or disturbance is required to cause a shift from one state to another, but the system then remains stable for decades to centuries. In the case of the milldam example, the construction and subsequent abandonment of the dams was the initial perturbation that drove the river system into a different configuration. The channels deeply incised into old milldam sediments are now stable and persistent and will remain so for the foreseeable future unless the sediments are physically removed via human intervention. Another example comes from beaver meadows, which are wet meadow complexes maintained by beaver dams. As long as the beavers are present, the dams facilitate overbank flows, the formation of secondary channels, and hyporheic exchange, all of which maintain a high riparian water table that favors riparian woody species such as *Salix* and *Populus*, which are preferred food for beavers (Rosell et al. 2005; Westbrook et al. 2006, 2011). If the beavers are removed for some reason, the dams fall into disrepair; and peak flows are more likely to be contained within a single channel, which typically widens and incises. This lowers the riparian water table and allows more xeric, upland plants to encroach on the valley bottom, which can stabilize as a drier grassland environment that ecologists sometimes call an elk grassland (Wolf et al. 2007). As in the milldam example, either beaver meadows or elk grasslands can persist for centuries in the same valley bottom, but some perturbation (e.g., removal or reintroduction of beavers) is needed to shift the river system from one stable state to another (Figure 50).

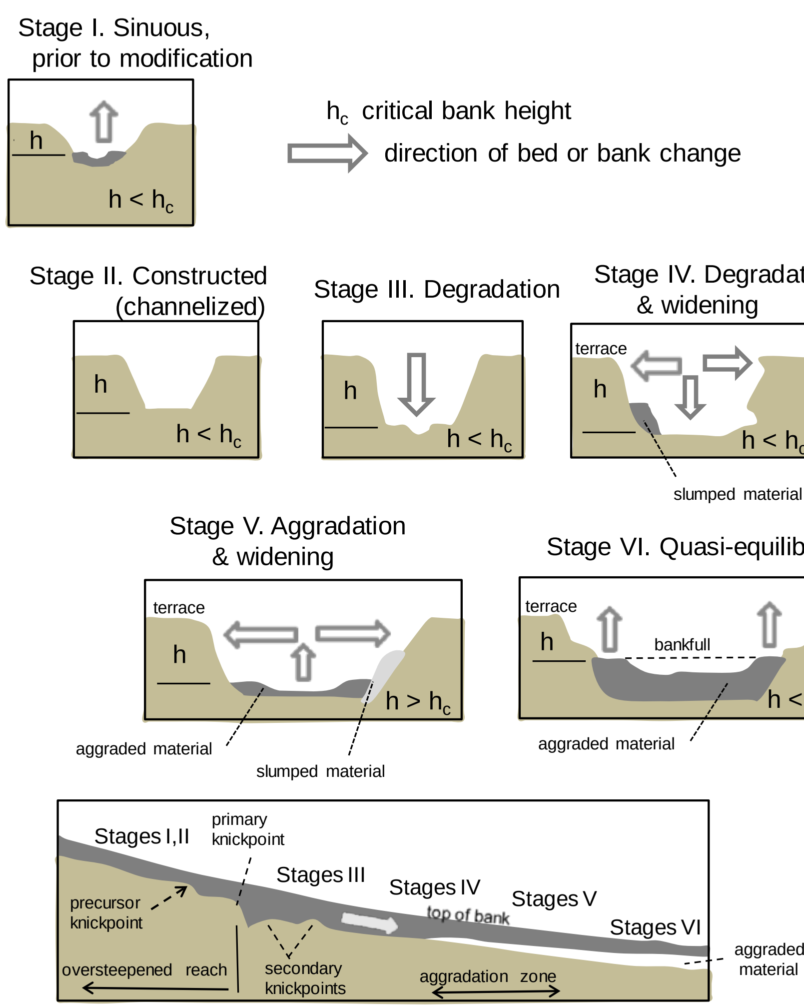
The existence of alternative stable states is relevant to the OHWM in that very different channel and valley forms may be present in rivers that are otherwise similar with respect to large-scale controls (lithology, soils, climate and flow regime, position in drainage network, etc.). This limits the ability to extrapolate regional relations for parameters such as the ratio of peak discharge to drainage area or peak discharge to channel dimensions.

Figure 50. Schematic illustration of alternative stable states for a valley bottom. Where beavers are present and maintain dams, beaver meadows persist. If beavers leave an area and dams fall into disrepair, the valley bottom can transition to a drier elk grassland.



Another important aspect of river response to diverse human modifications is the potential for downstream change of a very different nature than the change that occurs within the modified reach. For example, channelization commonly results in accelerated erosion of the channel bed and banks within the channelized reach. The excess sediment resulting from this channel erosion can result in channel narrowing and aggradation—accumulation of sediment—downstream from the channelized zone (Figure 51). Similarly, flow regulation that results in a sediment deficit downstream from a dam can cause channel erosion immediately downstream from the dam; but the sediment eroded from this proximal river reach can be deposited farther downstream where sediment supply exceeds river transport capacity. Wohl et al. (2015) discuss for a river reach the concept of a balanced sediment regime, which exists when flow is just sufficient to transport sediment supplied to the river reach. Flow regulation or changes in land cover, channel geometry, or riparian vegetation that alter the sediment regime in one portion of a river can create a form of chain reaction in which river reaches farther downstream react in a different manner, depending on the change in sediment supplied (increased or decreased) to these downstream reaches. This phenomenon was described as early as the 1970s and is referred to as *complex response* (Schumm and Parker 1973).

Figure 51. Illustration of a six-stage channel evolution model. Illustrations of stages I to VI feature upstream or downstream views. The lower box contains a longitudinal profile that illustrates different stages of channel adjustment occurring simultaneously along a channel. *Light brown shading* is valley sediment or bedrock, and *gray* is recent alluvium (modified from Simon and Castro 2003, Fig. 11.11, and Wohl 2010b, Fig. 4.14)



7 Examples of the OHWM in Diverse Regions

This section provides descriptions and illustrations of diverse hydroclimatic regions and positions within a river network, including those where it can be particularly challenging to distinguish the OHWM. Examples of particularly challenging environments in which to distinguish the OHWM include braided rivers, karst terrains, boulder fields, intermittent rivers, prairie rivers, distributary channels on alluvial fans and deltas, and compound channels. For most of these channels, the difficulty of delineating the OHWM makes it particularly appropriate to use the approach of bracketing the elevation of ordinary high water by using indicators that are characteristically above, at, and below the OHWM (Tables 2 and 3).

One consideration relevant to any type of channel is the situation that can occur at a confluence where a tributary joins a larger river. During floods, water from the larger river can flow into the tributary mouth and some distance up the tributary. These mainstem backwaters commonly have low velocity but can create higher depositional indicators of OHWM than do flows in the tributary channel. In this scenario, the indicators created by the mainstem backwaters define the OHWM for the affected portion of the tributary channel.

7.1 Channel classifications

River channels can be classified based on diverse criteria, including flow regime, bedforms, cross-sectional geometry, planform, position within the network, or substrate (Table 11). Classifying rivers by flow regime emphasizes differences in the magnitude, frequency, and duration of flow. Classifications based on bedforms have been designed for rivers in mountainous regions in which bedforms reflect reach-scale channel gradient, substrate grain size, and sediment transport capacity of the flow. The progression from cascade channels at the highest gradients to dune-ripple channels at the lowest gradients represents progressively decreasing grain size and greater transport capacity relative to the grain sizes available (Montgomery and Buffington 1997). Classifications of cross-sectional geometry focus on characteristics such as bankfull channel width-to-depth ratio (Rosgen 1994), with the assumption that differences in cross-sectional geometry correspond to differences in reach-scale gradient, grain size, and channel response to disturbance.

Table 11. Criteria used to classify river channels

Basis for classification	Example categories	Sample references
Flow regime	harsh intermittent intermittent flashy intermittent runoff perennial flashy perennial runoff snowmelt snow plus rain winter rain mesic groundwater	Poff and Ward (1989); Poff (1996)
Bedforms	cascade step-pool plane-bed pool-riffle dune-ripple	Montgomery and Buffington (1997)
Cross-sectional geometry	A through G	Rosgen (1994)
Planform	straight meandering anabranching braided	Leopold and Wolman (1957) Parker (1976) Schumm (1981) Wohl (2014c)
Position within network	headwaters intermediate large floodplain	
Substrate	clay-bed sand-bed gravel-bed bedrock	Wohl (2014c)

Classifications based on planform emphasize differences in the form assumed by a river when viewed on a two-dimensional planar surface such as a map. This is arguably the most commonly used characteristic for classifying channels. Numerous iterations exist, but a basic distinction can be made between single-thread channels and channels with multiple flow paths. Single channels are further subdivided based on sinuosity, which is the ratio of river length to a straight-line-distance parallel to the river. Rivers less sinuous than 1.5 are straight, and those with higher sinuosity are meandering (Leopold et al. 1964). Channels with multiple flow paths can be braided channels in which flow is separated by bars within a defined channel or anastomosing channels in which individual channels are separated by vegetated or otherwise stable islands and non-fluvial surfaces that are broad and long relative to the width of the channel and that divide flows at discharges up to bankfull (Nanson 2013).

Classifications with respect to position in the river network typically differentiate small or headwater channels; intermediate rivers; and large, lowland rivers although the criteria for differentiating these or other subdivisions vary widely among individual classifications.

Classifications that focus on channel substrate commonly emphasize how differences in the channel bed reflect differences in sediment supply and influence cross-sectional geometry and channel stability. Categories include clay-bed channels with cohesive sediment that require relatively large hydraulic force to erode the channel; sand-bed channels that respond quickly to changes in flow energy and are relatively resilient; gravel-bed channels with beds composed primarily of pebble- to boulder-size sediment, which have higher resistance to erosion and less resilience; and bedrock channels formed primarily in lithified material, which have the largest erosional thresholds and the lowest resilience (Baker 1988; Wohl 1998, 2014c; Whipple et al. 2013).

7.2 Headwater channels

As noted earlier, headwater channels have different definitions in terms of their stream order but are commonly considered to be only first order (Nadeau and Rains 2007), first and second order (Gomi et al. 2002; Benda et al. 2005; Freeman et al. 2007), or first to third order (Adams and Spotila 2005) channels. Other definitions of headwater channels focus on channel width (e.g., Wipfli et al. 2007). Small channels receive storm runoff relatively quickly but have limited drainage area to contribute groundwater. Consequently, headwaters are more likely than larger rivers to be ephemeral or intermittent, even in relatively wet climatic regions. In headwater channels that flow infrequently, fluvial erosional, depositional marks, and the OHWM may be obliterated or obscured by non-fluvial processes such as sheetwash or debris flows. The OHWM is likely to be contained within the active channel in headwaters, which seldom have well-developed floodplains.

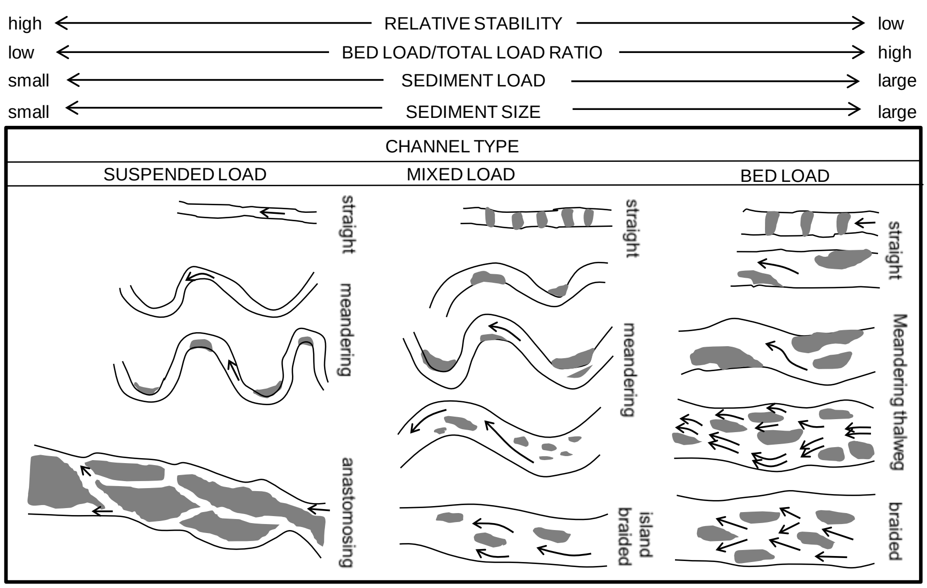
As small channels closely connected to water, sediment, and solute inputs from adjacent uplands, headwater channels are the first portion of the channel network to receive increases in water and sediment yield associated with natural or anthropogenic disturbances (Benda et al. 2005). They are also the portion of the river network most readily obliterated when topography is altered by land uses such as mining or when rivers are converted to subsurface storm drains in urban areas.

In mountainous areas, headwater channels typically do not exhibit progressive downstream trends in channel geometry but are instead likely to have abrupt longitudinal changes associated with reach-scale controls on gradient, valley geometry, and sediment supply (Adams and Spotila 2005; Wohl 2010b; Church 2013; Chappell and Brierley 2014). Mountainous headwater channels are also subject to periodic natural disturbances, such as debris flows and flash floods, that scour sediment and large wood from the channel (Gomi et al. 2002; Benda et al. 2005; May and Lisle 2012) and remove the OHWM and create extraordinary HWMs.

7.3 Straight channels

Single channels with a sinuosity less than 1.5 can form where a river is closely confined by steep valley walls or other upland surfaces such as terraces or by geologic structures or lithologic contracts. Straight channels can also form in erodible, alluvial materials; they remain straight because the banks have sufficient erosional resistance relative to available flow energy to limit bank erosion (Paola 2001). Straight channels can be further subdivided into those with alternating bars and a sinuous thalweg (line of deepest flow) and those with slightly sinuous channels with point bars (Figure 52). OHWMs can be contained within straight channels or can extend beyond the bankfull channel onto the adjacent floodplain.

Figure 52. Illustration of relationships among straight, meandering, and braided channels in terms of relative stability, the proportion of sediment transported as bedload, the relative amount of sediment transport, and the relative size of sediment. *Gray shading* indicates depositional areas in the form of islands, bars, or riffles. *Arrows* indicate flow paths (after Schumm 1981)

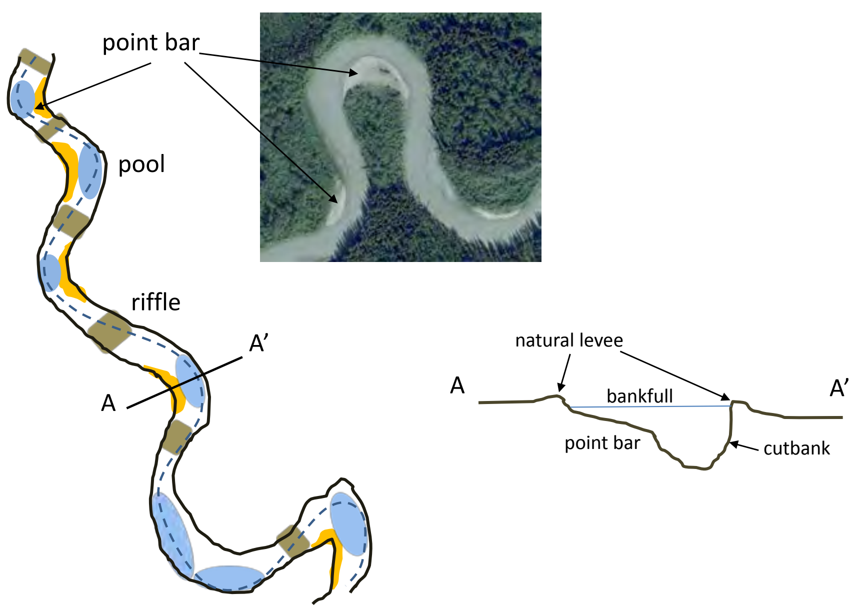


These channels can respond to changing water and sediment inputs in diverse ways, including changes in bed grain size, type and dimensions of bedforms, cross-sectional geometry (e.g., width-to-depth ratio), and reach-scale gradient. With greater changes in water and sediment entering the channel, a straight channel can become meandering, braided, or anastomosing or can move laterally across the floodplain.

7.4 Meandering channels

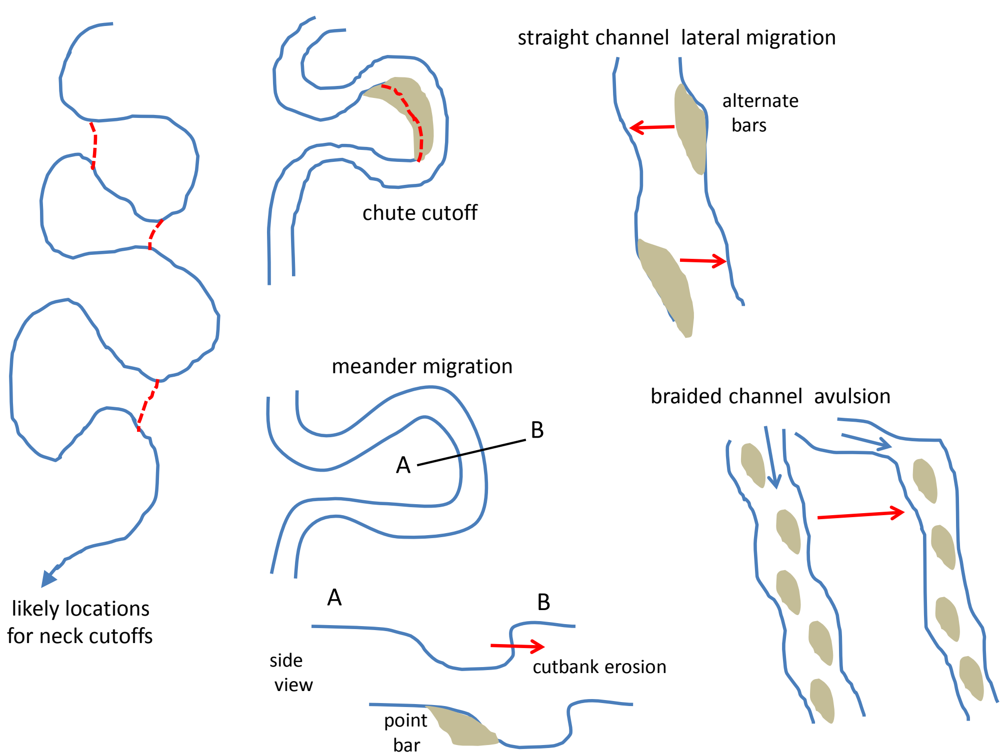
As noted above, meandering channels have a sinuosity greater than 1.5. Meandering is the most widespread and common channel planform (Leopold 1994) although straightening and channelization were used to modify many meandering rivers within the United States during the twentieth century. Within each meander, the outer bank is commonly steep and eroding with a pool present at the bend apex. Cross-sectional bed topography slopes downward from the point bar on the opposite inner bank. Riffles are present in the inflection regions of the bend, in the straight lines between successive bend apices, where cross-sectional and bank geometry are more symmetrical (Hooke 2013) (Figure 53).

Figure 53. Illustration of locations of pools (*blue shading*), riffles (*brown shading*), point bars (*orange shading*), and thalweg (*dashed line*) in meandering channels. Cross-sectional view illustrates bend asymmetry.



Important characteristics of meandering rivers in the context of the OHWM include cross-sectional asymmetry, super-elevation of the water surface during floods, and lateral channel movement. The cross-sectional asymmetry described above implies that the lateral distance of the OHWM from the center of the channel will be greater on the inside of each bend than on the outside. Super-elevation occurs when the water surface on the outside of a channel bend is higher than the water surface on the inside of the bend. Super-elevation is a function of flow velocity, bend geometry (radius of curvature), and channel width and is likely to be most pronounced at high velocities (Chow 1959). The occurrence of super-elevation during floods implies that the OHWM will be slightly higher on the outside of a channel bend. Lateral channel movement is an inherent characteristic of meandering rivers, with bank erosion along the outside of each bend and point-bar deposition on the inside of each bend tending to shift the channel sideways through time. Much of this movement occurs during floods. Individual meanders can migrate progressively or move abruptly through chute or neck cutoffs (Figure 54). In a meandering river segment that is stable in terms of reach-scale morphology, some bends become progressively more pronounced (increasing sinuosity) while other bends cut off (decreasing sinuosity) so that reach-scale sinuosity does not change progressively through time.

Figure 54. Schematic plan view illustrations of styles of channel migration, including neck and chute cutoffs, meander migration, lateral erosion and deposition, and avulsion. *Red arrows* indicate the direction of channel change with time. *Blue arrows* indicate flow direction.



Changing water and sediment inputs can result in a similar suite of responses to those described for straight channels: altered bed grain size, bedforms, cross-sectional geometry, reach-scale gradient, planform, or the location within the floodplain.

7.5 Braided rivers

Braided rivers have multiple secondary channels that branch and rejoin downstream around bars. The entire set of secondary channels constitutes the active channel (e.g., Moretto et al. 2014). Some of the bars can be submerged at high flows, but all are typically exposed at low flows. The degree to which the bars are vegetated varies, but the usual distinction between braided and anastomosing rivers is that bars in braided rivers have limited vegetation, are narrow relative to the width of the wetted channels, and are relatively mobile. The mobility of individual bars and secondary channels is a key characteristic of braided rivers, which are continually changing their channel geometry and location within the floodplain.

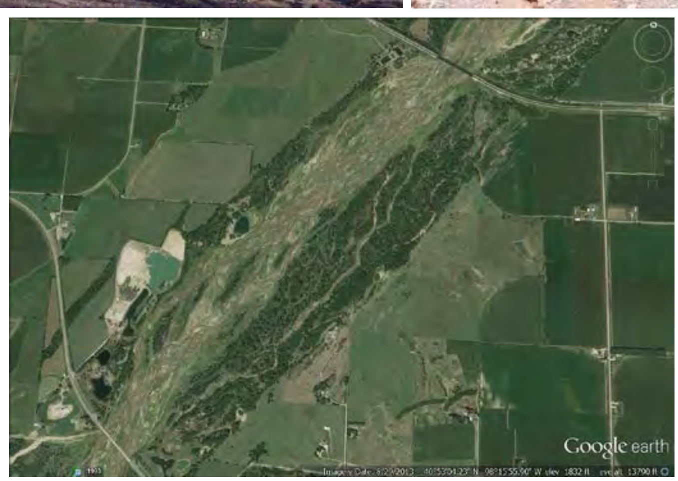
Braiding results from deposition of bed-material sediment along the bed and bank erosion during high flows and from dissection of bars during low flows (Ashmore 2013). Braiding is the most common channel planform in rivers lacking sufficient riparian vegetation or cohesive bank sediments to substantially increase bank resistance to erosion (Paola 2001). Braided rivers are associated with four conditions although no single condition is either sufficient or necessary to create a braided channel (Knighton 1998): (i) abundant bedload can cause braiding if the channel cannot transport the volume of sediment supplied; (ii) erodible banks facilitate continued channel widening and the development of multiple bars in wide, shallow flow; (iii) rapid fluctuations in discharge contribute to bank erosion and bedload transport that varies through time and across the channel; and (iv) steep valley gradients appear to promote braiding. Consequently, braiding characterizes rivers in arid and semiarid regions (Figure 55), mountainous environments with substantial inputs of coarse sediment such as those from landslides or debris flows, and rivers downstream from glaciers (Wohl 2014c).

Figure 55. Examples of braided rivers. (*A*) In high-latitude regions with or without glaciers upstream. (*B*) Ephemeral braided rivers in arid regions. (*C*) A Google Earth view of the Platte River near Phillips, Nebraska, which is gradually changing from being braided to anabranching (especially along the right side of the river corridor in this view) because of flow regulation and encroachment of riparian vegetation.

A

B

C



As with other channels, the OHWM in braided rivers can be contained within channels or can extend across the entire floodplain. The continual changes in channel geometry and location within braided-river corridors, however, make it particularly challenging to relate a surveyed OHWM to a particular flood magnitude, or vice-versa, and create uncertainties in delineating the active channel.

7.6 Anastomosing channels

Anastomosing channels, sometimes also known as anabranching channels, have multiple subparallel channels separated by vegetated or otherwise stable islands and non-fluvial surfaces that are broad and long relative to the width of the channels and that divide flows at discharges up to bankfull (Nanson 2013) (Figure 56). Islands within anastomosing channels persist for decades to centuries and are similar in elevation to the floodplain (Knighton 1998). Individual anastomosing channels can be straight or meandering; but unlike distributary networks, the channels in an anastomosing network eventually rejoin downstream. Anastomosing channels were more common prior to river engineering via levees, channelization, straightening, and removal of large wood (Pisut 2002; Latrubesse 2008; Wohl 2014a); but some examples still occur within the United States, such as Oregon's Willamette River (Sedell and Froggatt 1984; Benner and Sedell 1997).

Figure 56. An anabranching portion of the Yukon River in central Alaska.

Anastomosing planform can develop within alluvial substrate in numerous ways. Anastomosing can develop as erosional channels scour into the floodplain during channel avulsion. Avulsion can be triggered by sediment accumulation within a channel, particularly where an obstruction such as a channel-spanning logjam creates a backwater effect (Abbe and Montgomery 2003; O'Connor et al. 2003; Wohl 2011). Rapid aggradation can also produce frequent avulsions and a network of channels in various stages of formation and abandonment that can be anastomosing (Nanson 2013). Individual channels can develop from mid-channel bars that become islands dividing the flow in previously wider channels, particularly in very low-gradient channels. Individual channels can also develop from delta progradation and modification of the distributary network (Nanson 2013). Anastomosing channels can also develop in bedrock substrates, with individual channels commonly associated with prominent joints in the bedrock.

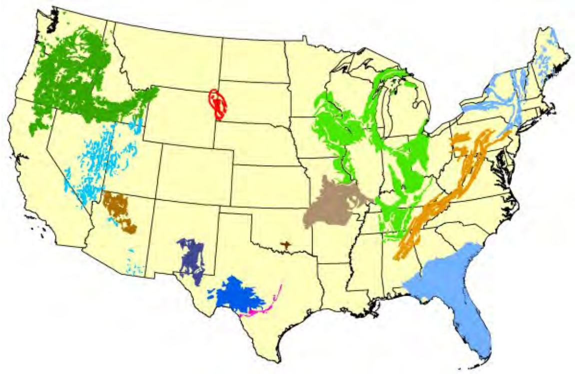
In the context of the OHWM, anastomosing channels can be complicated for at least two reasons. First, ordinary high water can be distributed among multiple channels spread across a floodplain with no clearly distinguishable primary or main channel. This results in widely dispersed OHWMs. Second, like braided channels, some anastomosing channels are characterized by frequent shifts in channel location and size, with associated transience of OHWMs.

7.7 Channels in karst terrains

As discussed in section 4.3, channels in karst terrains can be very challenging environments in which to delineate the OHWM because of complex relationships between surface channels and subsurface flow conduits (Figure 57). Surface channels can end abruptly in sinks or a blind valley where water enters subsurface flow paths. Surface channels can also start abruptly in large springs or a pocket valley where a subsurface flow conduit intersects the surface. The most complicated scenario involves a dry valley, or a channel in which base flow is carried underground, where storm runoff that exceeds some volume of discharge creates surface flow. In any of these scenarios, channels in a karst terrain may have HWMs that relate only to much larger and less frequent (extraordinary) flows than otherwise analogous channels in the region that have predominantly surface drainage. Karst terrains in the United States occur within arid and semiarid regions such as New Mexico but tend to be most well-developed within portions of the Appalachians (Kentucky and West Virginia), the Midwest (Indiana and Missouri), and Florida (USGS 2012) (Figure 57).

Figure 57. (*A*) Map of karst regions in the United States (USGS 2012). (*B*) Example of the entrance to an underground portion of a stream that flows for several hundred meters belowground before reemerging at the surface. The entrance shown here is about 3 m high.

A



B

7.8 Channels in boulder fields

Weathering of bedrock in mountainous environments with relatively cold or dry climates can create abundant boulders that form boulder fields and talus slopes. Boulder fields and talus slopes have cobbles and boulders with relatively little finer-grained sediment between the large clasts. Consequently, channels flowing into and through these sites may lose surface definition as water moves below the ground surface or at least at the base of the coarse layer of cobbles and boulders. At these sites, it is not uncommon to hear water flowing beneath the surface layer of boulders, even though no clearly defined channel is visible at the surface. Delineating the OHWM is obviously extremely challenging in this scenario even though a channel likely exists beneath the upper layer of boulders. Probably the simplest approach is to delineate the channel and OWHMs upstream and downstream from the boulder field where the channel is clearly present at the ground surface. Channels in boulder fields and on talus slopes are likely to be relatively small headwater channels and may also go dry seasonally. Examples of channels that include boulder fields have been described for the Southern Appalachian Mountains (Adams and Spotila 2005) and Washington's Cascade Range (Weekes et al. 2015).

7.9 Intermittent rivers

Intermittent rivers in which flow is discontinuous through time or along a given flow path are most likely to occur in very small drainage basins with limited groundwater recharge to support base flow or in arid and semiarid regions in which a lack of precipitation combined with relatively poor soil development and sparse vegetation limit groundwater and base flow to rivers. Some of the best-documented examples come from the Great Plains and western prairies of the United States where smaller rivers can have longitudinally continuous flow during periods of rainfall or snowmelt runoff only to shrink back to alternating wet and dry reaches during drier seasons of the year (Figure 58). These intermittent rivers have received particular attention because of the endangered fish species that rely on them for habitat, as well as the vulnerability of these channels to declining groundwater levels associated with groundwater pumping for agricultural or other consumptive uses (Falke et al. 2010). Because many of these channels drain relatively small areas in dry climates with substantial interannual variability in precipitation, periodic large floods can reconfigure channel geometry and create persistent HWMs that can sometimes obscure the OHWM created by more common, seasonal high flows along some channels. Intermittent rivers are not only small, however; medium to large rivers in dry climates can also be intermittent, either naturally or because of consumptive water use (e.g., the Colorado River near its delta in the Gulf of California).

Figure 58. An example of an intermittent channel in the shortgrass prairie of eastern Colorado. The Arikaree River has a longitudinally continuous channel but only disconnected pools of water during dry seasons, such as late summer, when these photos were taken.

7.10 Prairie rivers

The prairie rivers of the United States can be subdivided into those associated with tallgrass prairies, mixed-grass prairies, or shortgrass prairies. Tallgrass prairies in the eastern portion of the Midwest—Illinois; Iowa; portions of Minnesota and Missouri; and eastern Texas, Oklahoma, Kansas, Nebraska, and the Dakotas—are characterized by continuous vegetation cover and relatively reliable seasonal precipitation. Regular fire can maintain grass-dominated vegetation communities where there is sufficient precipitation to support woody vegetation (Briggs et al. 2005). The mixed-grass prairies of the western Dakotas; eastern Montana and Wyoming; and portions of Nebraska, Kansas, Oklahoma, and Texas occupy a transitional zone in terms of climate, grass species, and the extent to which vegetation covers the surface. The shortgrass prairies of western Nebraska, Kansas, Oklahoma, and Texas and eastern Colorado have exposed patches of bare soil between bunchgrasses and cacti and have higher rates of evaporation than precipitation, creating a semiarid climate with substantial interannual variability in precipitation and stream flow.

Smaller rivers of the tallgrass prairie were historically diffuse swales with poorly defined active channels and extensive overbank flooding during certain seasons of the year (Wohl 2013b) (Figure 59). Many of these rivers were channelized as part of agricultural land drainage during the nineteenth and twentieth centuries (Rhoads et al. 2003), creating more defined channels and OHWM levels. The larger rivers of the tallgrass prairie also had extensive flooding and regular inundation of the floodplain each year; but flow regulation, levee construction, and channelization have also created more-confined channels and well-defined OHWMs along these rivers (Wohl 2013b).

Smaller rivers of the shortgrass prairies are likely to be intermittent or ephemeral and to alternate through time between braiding and meandering planform (Friedman and Lee 2002) or to alternate through time and along a given flow path between relatively poorly defined swales and deeply incised arroyos (Schumm and Hadley 1957; Schumm and Parker 1973) (Figures 60–62). Each of these scenarios can present challenges to delineating the active channel and the OHWM because of the propensity for channel geometry and location to change rapidly in response to large floods.

Figure 59. Examples of tallgrass prairie channels on the Konza Prairie near Manhattan, Kansas. *Lower* photos show a perennial spring-fed reach of a headwater tributary to the South Branch of Kings Creek.

Figure 60. Examples of shortgrass prairie channels. The South Platte River in eastern Colorado is now a single channel lined by riparian woodlands. Prior to flow regulation, the channel was braided and had minimal woody vegetation. The *lower* photo mosaic illustrates the extent of the former active channel when the river was braided.

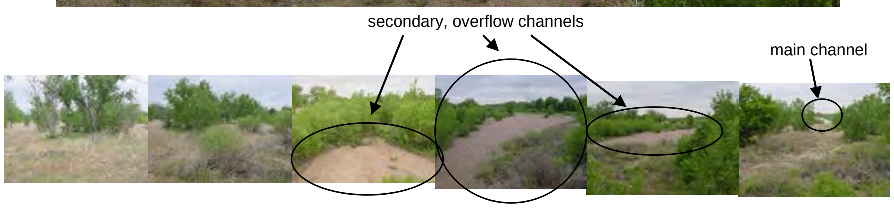


Figure 61. Example of a shortgrass prairie channels: South Pawnee Creek, a tributary of the South Platte River, in Pawnee National Grassland, Colorado. This creek dries back to disconnected pools for much of the year, but rainfall can bring floods that briefly reconnect the pools into a continuous stream.

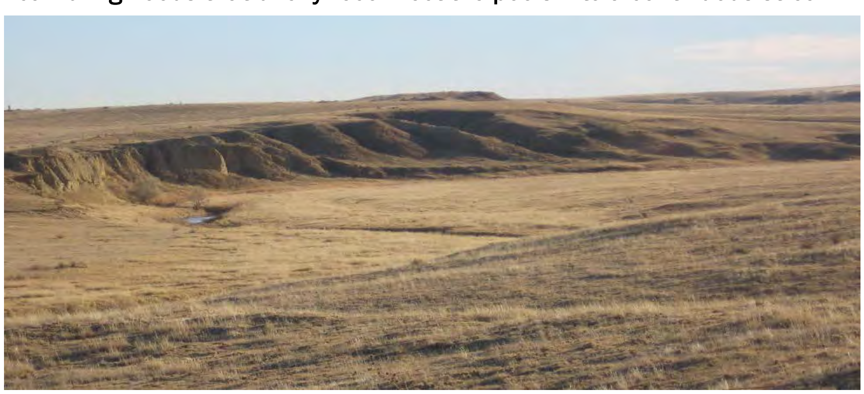


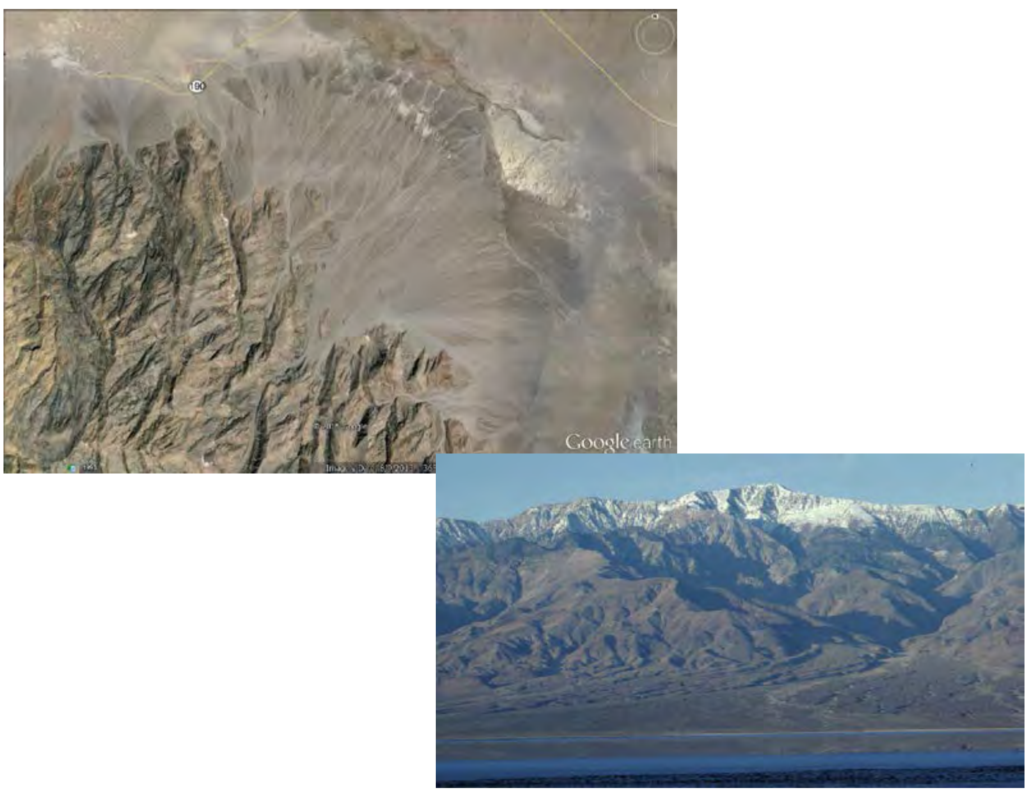
Figure 62. Examples of shortgrass prairie channels: refuge pools on the Pawnee National Grassland, Colorado. Sometimes the pools retain water through the year; but at other times, the pools go dry (both photos taken in autumn).

7.11 Distributary channels on alluvial fans and deltas

Distributary channels are those that branch from a main channel and then do not rejoin the main channel because flow in the channel dissipates either through infiltration and evaporation (alluvial fans) or through mixing with a body of receiving water (deltas). Both alluvial fans and deltas are primarily depositional environments formed where sediment transport capacity in a channel declines.

Alluvial fans typically form where a channel flows from a steep, laterally confined valley within a mountain range onto an alluvial basin or other lowland (Figure 63). Lower transport capacity as a result of lower downstream gradient; greater channel width; and in dry regions, infiltration and evaporation of flow, creates the fan. Deposition on the fan can occur during river flow, debris flows, rockfall, landslide, and snow avalanches, depending on the specific location of a fan; but the primary characteristic of alluvial fans is repeated deposition (Stock 2013). This continuing deposition creates aggradation, overbank flows, channel avulsion, and sheetflooding (Graf 1988; Blair and McPherson 2009). Inactive alluvial fans can have incised and relatively stable channels. Active alluvial fans are difficult environments in which to delineate the OHWM because of both the propensity for changes in channel geometry and location and the tendency for even ordinary high water to overtop channel banks and spread widely across the fan surface.

Figure 63. Google Earth view of distributary alluvial-fan channels in Death Valley, California, and a ground view of another alluvial fan in Death Valley.



Deltas form where a channel enters a body of standing freshwater, such as a lake, or where a channel enters the ocean. Like an alluvial fan, a delta is primarily a depositional feature that results from decreased flow velocity and confinement. A delta can protrude well beyond the adjacent coastline when a river carries large volumes of sediment that currents in the receiving body of water have limited capacity to rework (Figure 64). A delta can also form primarily upstream from the adjacent coastline where the entering river carries limited sediment or the receiving body of water has sufficient waves, tides, or currents to rapidly erode and transport the river sediment.

Figure 64. Google Earth view of the Yukon River delta in Alaska, showing the network of distributary channels.

Like alluvial fans, deltas are inherently dynamic environments in which deposition on one portion of the delta is likely to promote aggradation, overbank flows, and channel avulsion (Slingerland and Smith 1998; Jerolmack and Mohrig 2007). An active delta typically includes subdeltas created where sediment diverted through breached natural levees accumulates as crevasse splays (Figure 65). Channels on the subdelta also split into distributaries and deposit sediment until avulsion occurs and deposition shifts to a new subdelta. On the Mississippi River, the formation and abandonment of subdeltas occur over a few decades (Morgan 1970). On the delta of the San Antonio River in Texas, avulsions within a limited area recur at intervals of approximately 20 to 40 years, but major avulsions across the delta recur at intervals of 300 years or less (Phillips 2012). The timescale for these processes reflects sediment load carried by the river and how quickly the deposited sediment subsides or is eroded by waves and tides.

Figure 65. Aerial view of a delta distributary with a natural levee (forested band along the channel) and crevasse splay (light colored sediment deposits at the center of the view). (Picture by H.J.A. Berendsen, courtesy of the University of Utrecht, The Netherlands, http://www.geo.uu.nl/fg/palaeogeography/results/avulsions)

An important difference between alluvial fans and deltas is that delta sediments tend to subside under their own weight as the pressure of overlying sediment reduces porosity and permeability and forces pore water out of the sediment. The effects of subsidence become pronounced once the site of active deposition shifts to another portion of the delta, and subsidence renders the delta more susceptible to erosion by waves and tides. Delta distributary channels also differ from alluvial-fan distributaries in that flow in marine delta channels can be bidirectional as water flows toward the ocean during low tide and then flows upstream during high tide. The potential for tidal bores or storm surges associated with hurricanes or cyclones can also create extraordinary HWMs that obscure the OHWM (Bartsch-Winkler and Lynch 1988). Deltas are challenging environments in which to delineate the OHWM because of the continual changes in channel geometry and location and the potential for unusual high flows generated by the receiving water body to obscure the OHWM.

7.12 Compound channels

A compound channel is commonly defined as a channel with distinct high- and low-flow portions that have different planforms during different seasons or as a channel that alternates between different planforms over longer periods. Fahnestock (1963) described a seasonally compound channel for a length of valley downstream from the glacier on Mount Rainier, Washington. The White River alternated seasonally between a low-discharge meandering channel and a braided river during high summer flows (Figure 66). Examples of channels with repetitive fluctuations in planform over longer time periods come from semiarid portions of the Great Plains in Colorado (Friedman and Lee 2002) and the semiarid plateaus of western Colorado (Jaquette et al. 2005). In each case, the channel assumes a braided planform after a large flood, gradually transforms to a meandering channel with riparian forests over several decades during which floods are smaller, and then again becomes a braided river during a large flood. Repeated changes in channel planform and cross-sectional geometry, whether occurring across seasons or decades, make it difficult to identify the OHWM. This is another channel type in which constraining a vertical range for the OHWM by delineating indicators above and below ordinary high water is likely to be the best approach.

Figure 66. An example of a compound channel. Imagery of the White River, draining northeast from Mount Rainier in Washington (toward the upper right in both views). (*A*) In July, the channel is braided whereas (*B*) in September, the channel assumes a single-channel, more sinuous planform. (Map data from Google, DigitalGlobe.)

A

B

8 The OHWM and Active Channel in Relation to Adjacent Areas of the River Corridor

The active channel that is filled with water on a relatively frequent basis is only a portion of a river corridor. We define the river corridor as the portion of any landscape that has been created by river erosion and deposition through time and that remains connected to the contemporary river at least during ordinary floods. The river corridor includes the active channel, the adjacent floodplain and the riparian zone, secondary and floodplain channels, the zone within which the active channel migrates, and the underlying hyporheic zone (Figures 67 and 68).

Figure 67. A schematic illustration of a river corridor, showing the lateral extent of the floodplain and riparian zone and the hyporheic zone in addition to the location of the main channel, a secondary channel and associated natural levees, and a floodplain wetland formed from an abandoned channel.

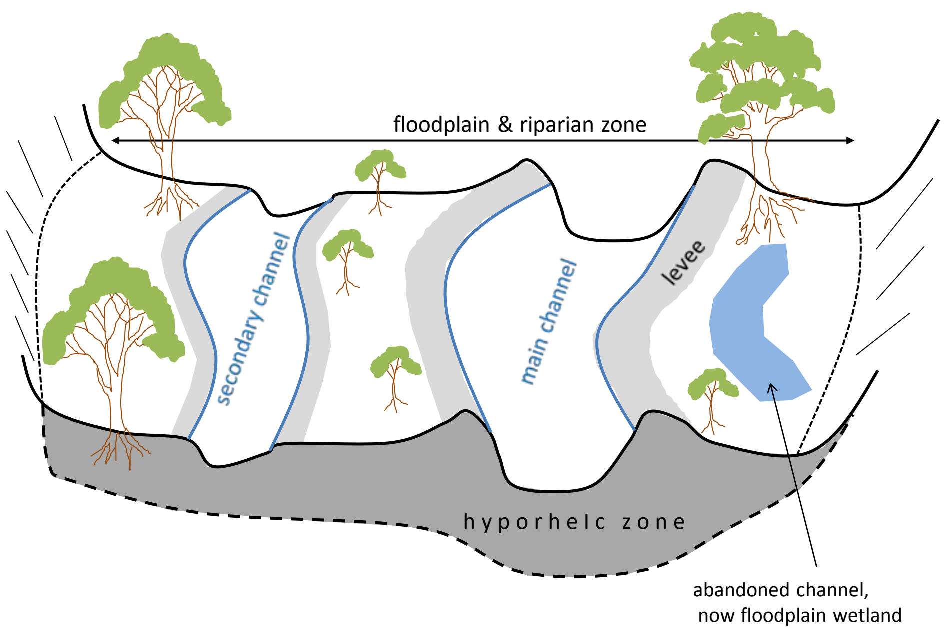
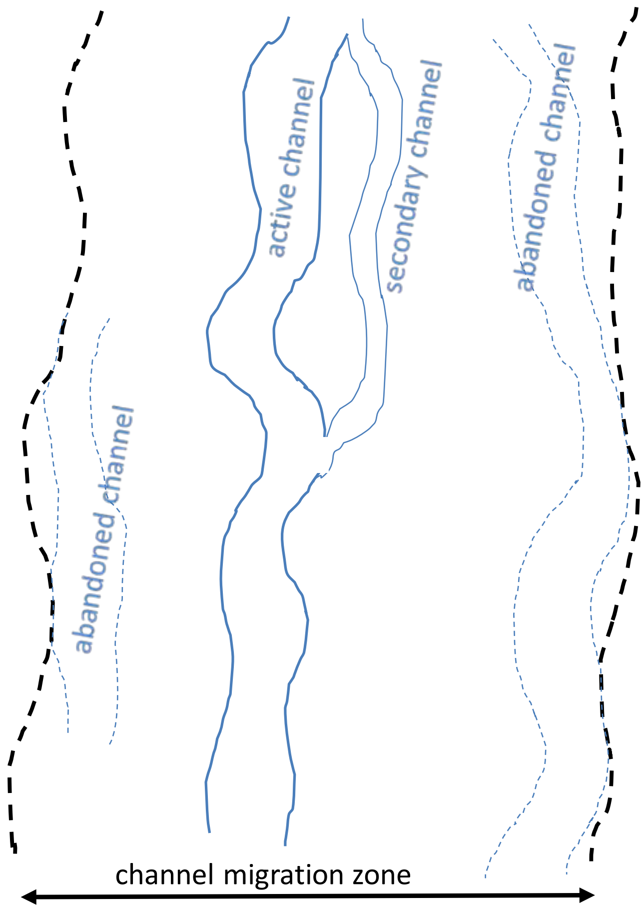


Figure 68. A plan view of the river corridor indicating the lateral extent of the channel migration zone.



8.1 The floodplain

Floodplains are relatively flat sedimentary surfaces adjacent to the active channel and are built by river processes and inundated frequently (Dunne and Aalto 2013). Engineers and regulators designate floodplains based on average recurrence intervals of flooding, as in the 10-year floodplain or the 100-year floodplain. Geomorphologists sometimes refer to such surfaces as the hydraulic floodplain (Nanson and Croke 1992) because all of the surface area inundated by a flood that recurs on average once every 100 years was not necessarily created by river processes. Individual papers within the geomorphic literature disagree as to what constitutes an active floodplain, but geomorphologists are more likely to describe floodplains as those surfaces that are flooded at least once every two years, with the assumption that such surfaces are composed largely of river sediments deposited under the current flow regime rather than relict river sediments deposited under very different conditions. Rivers with extremely variable hydrologic regimes, such as those in arid climates, can have flat surfaces adjacent to the active channel that are composed of river sediments deposited under the current flow regime but that are flooded much less frequently than once every 2 years—even as infrequently as once every 30 years (Williams 1978a). Floodplains are typically located above or outside of the OHWM; and where a geomorphic floodplain is present, the OHWM generally occurs at the boundary between the active channel and the floodplain. However, where ordinary high water overtops the banks of the active channel, the OHWM may include a portion of the floodplain that is flooded more years than not.

8.2 The riparian zone

The riparian zone refers to the interface between terrestrial and aquatic ecosystems (Naiman et al. 2005). The Corps defines riparian areas as "lands adjacent to streams, lakes, and estuarine-marine shorelines. Riparian areas are transitional between terrestrial and aquatic ecosystems, through which surface and subsurface hydrology connects riverine, lacustrine, estuarine, and marine waters with their adjacent wetlands, non-wetland waters, or uplands" (USACE 2012). Riparian zones can be difficult to delineate because they include features as diverse as depressions that create floodplain wetlands and higher-elevation natural levees. The lateral extent of the riparian zone can also be defined as the surface extent of frequent flooding and the subsurface extent of the mixing of river, hyporheic, and groundwaters (Wohl 2014c) (Figure 67A). Riparian zones thus have substantial overlap with floodplains; but *riparian zone* is primarily an ecological concept, and *floodplain* is primarily a geomorphic and hydrologic concept. Riparian zones can occur in portions of the river network that do not have floodplains, such as steep-sided, narrow valleys. Ecologists have also used ecological resource subsidies from rivers to the surrounding environment (e.g., emergent aquatic insects preyed on by birds) to delimit the biological stream width, which does not necessarily correspond to hydrological delimitations of the riparian zone (Muehlbauer et al. 2014).

The characteristics of the riparian zone and particularly of the vegetation within this zone strongly influence water and sediment entering the active channel and moving downstream within the active channel. Subsurface water coming from the riparian zone commonly precedes peak flow in the river as recharge in the uplands drives subsurface flow into the channel (McGlynn and McDonnell 2003). Vegetated riparian zones can effectively trap and store sediment of sand size or finer that is being transported by overland flow or overbank flows from a channel (Hickin 1984; Griffin et al. 2005; Naiman et al. 2005). Riparian vegetation also helps to stabilize the banks of the active channel (Allmendinger et al. 2005; Tal and Paola 2007; Merritt 2013). Woody riparian vegetation can be an important source of large, downed wood (>10 cm diameter and 1 m length) to channels and floodplains (Benda and Bigelow 2014). Large wood in turn creates numerous physical and ecological effects in rivers, including altering velocity, depth, sediment transport, bedform type and dimensions, and channel planform (Brooks et al. 2003; Curran and Wohl 2003; Collins et al. 2012; Gurnell et al. 2012); increasing nutrient retention and biological uptake (Naiman et al. 2010; Beckman and Wohl 2014); and increasing habitat diversity, biodiversity, and biomass within channels and riparian zones (Harmon et al. 1986; Benke 2001; Nagayama et al. 2012). By influencing the resistance to erosion of the active-channel boundaries and also the hydraulic roughness, flow velocity, and flow depth, riparian vegetation strongly influences the elevation of the OHWM.

Riparian buffer zones are designated with the intent of preserving the physical and ecological functions provided by the riparian zone. This practice originated in areas with timber harvest and then expanded to areas with agriculture, urbanization, and other land uses (e.g., Dosskey et al. 2006; Clinton 2011). Effectively delineating the spatial extent of riparian processes into management guidelines has proven to be challenging, and diverse agencies use slightly different guidelines based on physical factors such as waterbody type, shoreline slope, and waterbody size and biological factors such as presence of fish (Lee et al. 2004). The extent to which riparian buffers are protected throughout a watershed can influence elevation and characteristics (e.g., plant species present) of the OHWM.

8.3 Secondary and floodplain channels

Secondary channels and floodplain channels are largely synonymous here and refer to subsidiary channels that branch from the main, active channel and trend parallel or subparallel to the main channel before rejoining it downstream. These channels are thus distinct from tributaries, which originate elsewhere and terminate in the main channel, or distributaries on a delta or alluvial fan that originate in the main channel and then terminate on the fan or delta.

Secondary channels can carry a portion of the base river flow throughout the year, particularly in a braided or anastomosing river. Secondary channels can also be dry except during peak flows. Additionally, they can form when a temporary or persistent obstruction (e.g., sediment deposit, beaver dam, or logjam) limits flow in the main channel and enhances overbank flows across the floodplain (Abbe and Montgomery 2003; O'Connor et al. 2003; Wohl 2011; Collins et al. 2012). Overbank flow across an irregular floodplain surface tends to concentrate in depressions or areas with more readily erodible surfaces, creating secondary channels. Secondary channels can also form when channel avulsion—rapid lateral movement by a channel, typically during a flood—leaves a partly abandoned channel that retains some hydrological connection to the main channel (Nanson 2013). Mid-channel bars that become islands and divide the flow in previously wider channels can also create secondary channels (Ashmore 2013; Nanson 2013). Braided and anastomosing planforms and other forms of secondary channels were much more common prior to intensive channelization to improve navigation or enhance flood conveyance (Pisut 2002; Latrubesse 2008; Nanson 2013).

In scenarios where all of the ordinary high water is contained within a main channel and secondary channels (as opposed to overtopping all of these channels), the existence of secondary channels implies that the OHWM usually must be designated in multiple places across a river corridor rather than in just two spots on either side of the main channel. Because secondary channels typically have lower flow velocity than the main channel, their presence can also complicate designation of an OHWM because the secondary channels can gradually accumulate sediment during lower flows and then erode and become larger during higher, faster flood flows.

8.4 The channel migration zone

The channel migration zone here refers to the width of the valley bottom across which main and secondary channels can migrate and have migrated under the contemporary (either natural or human-altered) streamflow regime (Figure 67B). The channel migration zone typically lies within the boundaries of the floodplain, but not always. A relatively common scenario in which the channel migration zone can extend beyond the floodplain is that of a braided river in an arid or semiarid region or downstream from a glacier. Braided rivers are inherently laterally mobile and subject to abrupt avulsions (Ashmore 2013) because of their erodible banks, high sediment loads, and fluctuating discharge. Particularly dramatic examples of lateral channel migration have occurred during extraordinary floods, such as the October 1983 flood in Tucson, Arizona, when portions of the length of the Santa Cruz River migrated so extensively that a new active channel was created outside of the previously designated 500-year flood zone (Kresan 1988). The relevance of the channel migration zone to the OHWM is that abrupt channel migration can create a completely new active channel and associated OHWM.

Table 12 summarizes rates of channel migration published for diverse rivers in the United States and Canada. All of the rates in this table represent values averaged over a period of at least several years, but most of the channel migration summed during a year or between years typically occurs during the relatively short duration of individual ordinary or extraordinary floods (Clayton and Pitlick 2008; Hood 2010; Sorrells and Royall 2014).

Channel migration in meandering channels typically involves erosion along the outside of each meander bend, with compensating deposition along the inside of the bend (Figure 54). Individual meander bends can also be cut off from the main channel by development of a chute cutoff across the top of the point bar or a neck cutoff across the base of the meander (Figure 54). Although the average sinuosity of a stable meandering channel does not change through time, individual bends can move substantially. The sinuosity of an unstable meandering channel can increase or decrease with time via migrations and cutoffs of individual bends.

Channel migration in braided, anastomosing, or straight channels can occur through cutbank erosion on one side of the channel, which is commonly associated with deposition on an alternate bar on the opposing bank (Figure 54). Channel migration in braided and anastomosing channels is also likely to take the form of avulsion in which rapid lateral movement creates a new channel.

Braided and anastomosing channels are characterized by repeated avulsions just as meandering channels are characterized by continual migration of individual bends; but the rates of bend migration and avulsion can change in response to changes in water or sediment yield to the channel, changes in base level, or changes in the erosional resistance of the channel substrate (e.g., changes in riparian vegetation or engineered stabilization of banks). Consequently, diverse human activities such as flow regulation, changes in land cover, and channel engineering can cause substantial changes in channel migration rates (Micheli et al. 2004; Gendaszek et al. 2012).

Table 12. Published rates of channel migration.

River	Drainage Area (km^2)	Description	Rate of Migration (m/year)	Reference
Merced River, CA	3305	meandering, S 0.002, Q_b 20.5 m^3/s, w_b 29 m, D_{50} 0.05 m; over 5 years	0.02 to 1	Harrison et al. (2011)
Mississippi River	3.2×10^6	meandering, historical migration rates over 47 years prior to channel engineering	45 with clay plugs 59 without clay plugs range < 0.1 to 123	Hudson and Kesel (2000)
Winooski R, VT Connecticut R, NH Genessee R, NY	2770 4295 3600	meandering, Q_a 51 m^3/s, S 0.0014, w_b 100 m, sand meandering, Q_a 46 m^3/s, S 0.00009, w_b 40–50 m, sand meandering, Q_a 52 m^3/s, S 0.0008, w_b 65 m, sand	0.7 3.1 4.7	Black et al. (2010)
Sacramento R, CA	68,000	meandering, Q_b 2000-2400 m^3/s, S 0.0002–0.0004, w_b 210–315 m, gravel and sand	4(range 0–10)	Constantine et al. (2009)
Upper Quinault R, WA Lower Quinault Queets R, WA	441 1124 1152	meandering to braided, S 0.0035, w 104–240 m, gravel-cobble meandering to braided, Q_a 41 m^3/s, S 0.0011, w 45–95 m, gravel-cobble meandering to braided, Q_a 123 m^3/s, S 0.0022, w 89–165 m, gravel-cobble	12.7 $\pm$ 3.3 4.0 $\pm$ 1.2 7.5 $\pm$ 2	O'Connor et al. (2003)
Sprague R, OR	4167	Variable, from boulder-bed confined to meandering sand-bed, Q_a 18 m^3/s, S 0.002 to 0.0002, w_b avg. 30 m	mostly < 0.5 but as much as 30	O'Connor et al. (2015)
Brazos R, TX	92,650	meandering, Q_p 1400 m^3/s, sand	0.6–5.5	Heitmuller and Greene (2009)
Ottawa R, OH	446	meandering, Q_a 5.3 m^3/s, S 0.0007, silt and clay	0.3	Evans et al. (2013)
Elkhead Cr, CO	475 589	meandering, Q_p 29 m^3/s, w_b ~ 15m, gravel-cobbles meandering, gravel-cobbles	avg. 0.6 (up to 4.3) avg. 0.8 (up to 3.3)	Elliott and Char (2012)
38 streams in Indiana		meandering	mostly < 0.3, but up to 9	Robinson (2013)
Cedar R, WA	477	anastomosing, Q_a 19 m^3/s, w_b 30–40 m, gravel	1.3 to 8	Gendaszek et al. (2012)
23 rivers in Alberta and BC, Canada (all meandering)	420 17,800 14,500 15,370 2,880 30,800 1,940 7,400 52,230 20,320 39,680 2,830 840 7,120 5,730 20,300	Q_p 36 m^3/s, S 0.0028, w_b 21 m, gravel Q_p 42 m^3/s, S 0.0003, w_b 32 m, sand Q_p 115 m^3/s, S 0.0002, w_b 44 m, gravel and sand Q_p 569 m^3/s, S 0.0018, w_b 117 m, gravel Q_p 108 m^3/s, S 0.0030, w_b 57 m, gravel Q_p 399 m^3/s, S 0.0002, w_b 126 m, sand Q_p 186 m^3/s, S 0.0001, w_b 28 m, gravel Q_p 320 m^3/s, S 0.0001, w_b 68 m, sand Q_p 3867 m^3/s, S 0.0003, w_b 288 m, gravel Q_p 1276 m^3/s, S 0.0005, w_b 163 m, gravel Q_p 506 m^3/s, S 0.0002, w_b 86 m, sand Q_p 65 m^3/s, S 0.0003, w_b 44 m, sand Q_p 92 m^3/s, S 0.0013, w_b 43 m, gravel Q_p 690 m^3/s, S 0.0001, w_b 123 m, sand Q_p 97 m^3/s, S 0.0007, w_b 74 m, sand Q_p 2161 m^3/s, S 0.0003, w_b 205 m, gravel	0.6 0.6 1.2 1.5 3 0.01 0.2 0.6 2.5 4.1 0.8 0.3 1.8 0.6 1.6 5.5	Nicoll and Hickin (2010)

River	Drainage Area (km^2)	Description	Rate of Migration (m/year)	Reference
	23,820	Q_p 778 m^3/s, S 0.0007, w_b 140 m, gravel	1.6	
	11,830	Q_p 511 m^3/s, S 0.0013, w_b 99 m, gravel	0.2	
	610	Q_p 58 m^3/s, S 0.0024, w_b 33 m, gravel	0.8	
	8,450	Q_p 1141 m^3/s, S 0.0008, w_b 142 m, gravel	3.3	
	35,280	Q_p 454 m^3/s, S 0.0003, w_b 140 m, sand	1.6	
	11,300	Q_p 1205 m^3/s, S 0.0012, w_b 139 m, gravel	5.8	
	1,560	Q_p 89 m^3/s, S 0.0026, w_b 39 m, gravel	0.9	
Rio Grande, NM	37,800	straight, w 90 m, gravel	0.2 to 10	Richard et al. (2005)
Beatton R, Canada		meandering, Q_p 225 m^3/s, S 0.0003, w 70 m, gravel	0.2 to 0.7	Hickin and Nanson (1975)
22 rivers in western OR (all straight)	900	S 0.0013, w 51 m	3.8	O'Connor et al. (2014)
	110	S 0.0021, w 18 m	1.1	
	1990	S 0.0028, w 33 m	3.2	
	2560	S 0.0019, w 55 m	1.0	
	13,310	S 0.0007, w 95 m	1.9	
	640	S 0.0009, w 24 m	1.4	
	494	S 0.0012, w 33 m	1.2	
	86	S 0.0040, w 13 m	1.4	
	110	S 0.0022, w 14 m	0.6	
	424	S 0.0016, w 29 m	0.7	
	167	S 0.0015, w 26 m	1.1	
	1840	S 0.0013, w 51 m	1.4	
	1370	S 0.0036, w 26 m	0.6	
	6470	S 0.0014, w 69 m	1.0	
	8890	S 0.0014, w 83 m	1.4	
	10,290	S 0.0020, w 54 m	1.1	
	490	S 0.0027, w 23 m	0.8	
	800	S 0.0015, w 24 m	0.7	
	750	S 0.0003, w 16 m	0.6	
	1960	S 0.0025, w 32 m	0.6	
	4660	S 0.0011, w 56 m	1.2	
	8930	S 0.0010, w 83 m	1.2	

S is channel gradient (m/m); Q_b is bankfull discharge; Q_a is mean annual discharge; Q_p is average annual peak discharge; w is channel width; w_b is average bankfull width, D_{50} is median bed grain size.

Diverse types of channel mobility, from individual bend migration to avulsion across a valley bottom, are important for maintaining the diverse habitat that can help to sustain biodiversity. In general, floodplains that are wide relative to the active channel tend to include more diverse habitats (Bellmore and Baxter 2014; Choné and Biron 2015) although modifications such as channelization and flow regulation can substantially reduce channel mobility and habitat and biodiversity (e.g., Karaus et al. 2013; Wyżga et al. 2014).

8.5 The hyporheic zone

The hyporheic zone is the portion of unconfined, near-stream aquifers where river water is present. Hydrologists define this zone as a flow-through subsurface region in which flow paths originate and terminate at the river. The hyporheic zone can extend up to 2 km laterally from the active channel along rivers with broad, gravel floodplains (Stanford and Ward 1988) and can extend several meters below large alluvial rivers. The length and travel time of flow paths within the hyporheic zone vary substantially, making it possible to designate 2-hour hyporheic zones, 10-hour, 24-hour, and so forth (Gooseff 2010), analogous to 2-year floodplains or 10-year floodplains. Hyporheic flow can constitute less than 1% of river discharge in steep, small channels with limited alluvium (Wondzell and Swanson 1996) but can account for 15% or more of surface discharge in larger, lowland alluvial rivers (Laenen and Risley 1997).

The location and rate of downwelling from the streambed into the hyporheic zone and upwelling from the hyporheic zone into the active channel depend on pressure gradients within the surface and subsurface flow and on the porosity and permeability of near-surface bed sediments (Tonina and Buffington 2009; Gooseff 2010). Downwelling typically occurs at obstacles to flow, such as instream wood or beaver dams, and bedforms, such as riffles and bars, with upwelling downstream from the obstacle or in pools (Buffington and Tonina 2009; Wondzell et al. 2009). Consequently, changes in the configuration of the active channel, including bedforms and bed sediments, influence the rate and location of hyporheic exchange. Conversely, changes in hyporheic exchange have the potential to influence the characteristics of the active channel and the discharge—and hence the OHWM—in some channels.

8.6 Methods of remotely estimating channel and floodplain dimensions and upstream extent of the channel network

There are at least two basic approaches to remotely measure and map the spatial extent (width) of the active channel, bankfull channel, floodplain, and channel migration zone over entire river networks or multiple networks. The first approach is to use remote imagery such as satellite images to delineate the extent of channel and floodplain edges. This can be facilitated by differences in vegetation communities or by topographic features discernible on the imagery but can be difficult in areas where land use has largely eliminated riparian vegetation or where topographic relief is very low. Satellite imagery has also been used in a variation of downstream hydraulic geometry known as at-many-stations hydraulic geometry (Gleason and Smith 2014). Using this approach with Landsat Thematic Mapper images for three rivers in North America and China, Gleason and Smith (2014) found that they could estimate river discharge to within 20%–30% of actual discharge as measured at gaging stations. Estimates of river discharge can in turn be related to likely channel dimensions and the elevation of OHWMs.

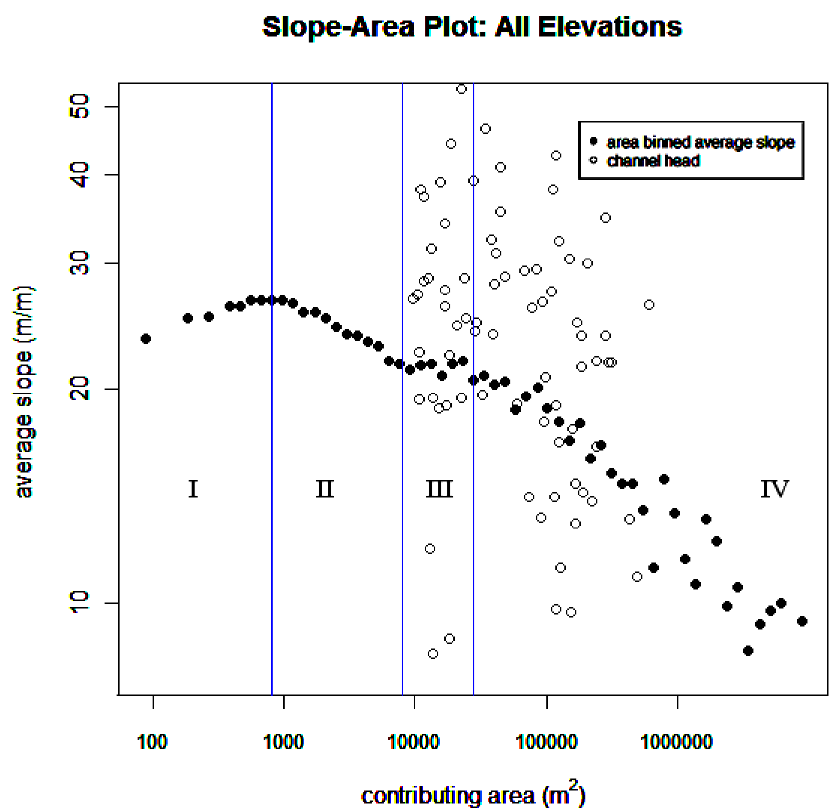
A variant of the use of satellite images and one that could be applied at the typically smaller spatial scales likely to be covered by high-resolution light detection and ranging (LiDAR) data is to use LiDAR imagery to detect the topography commonly associated with the active channel, floodplain, and channel migration zone. As higher-resolution LiDAR imagery becomes increasingly available within the United States, this method holds great promise for accurate delineation of channel boundaries.

The second basic approach is to use the U.S. Geological Survey National Hydrography Dataset (NHD; http://nhd.usgs.gov/) for rivers in the United States and to either measure parameters directly from this dataset or assume some consistent scaling relation. An example of directly measured parameters comes from a study of the extent and duration of lateral hyporheic exchange throughout the Mississippi River network (Kiel and Cardenas 2014). Kiel and Cardenas measured channel width from NHD river polygons at every 1.5 km along the network. An example of using a scaling relation comes from a study using field surveys and NHD digital stream trace data for 2162 sites within the United States. Hughes et al. (2011) found that Strahler (1957) stream order provided a useful approximation of the ranges of field-based low-flow and bankfull channel widths for most streams within a given stream order. However, Hughes et al. (2011) also found that, even with physically (e.g., geology and climate) and ecologically similar regions, site-specific predictions of stream size based on stream order can have large errors.

Remote estimations of channel and floodplain dimensions can facilitate comparisons of mean values and ranges between diverse rivers and regions and comparisons between different types of feature (e.g., active versus bankfull channel) at diverse sites. These types of cross-site comparisons may eventually lead to useful predictive relations for channel and floodplain dimensions.

Delineating the upstream extent of the channel network requires locating channel heads. In the absence of field-based data, a common default assumption is that channel heads lie near reversals or inflections in averaged hillslope profiles (Ijjasz-Vasquez and Bras 1995) although this can result in significant over- or underestimations of drainage area (Tarolli and Dalla Fontana 2009; Henkle et al. 2011) (Figure 69). Because channel heads are commonly small in size and difficult to detect on remote-sensing imagery, field-based mapping of the distribution of channel heads remains the most reliable mechanism for delineating the upstream extent of the channel network.

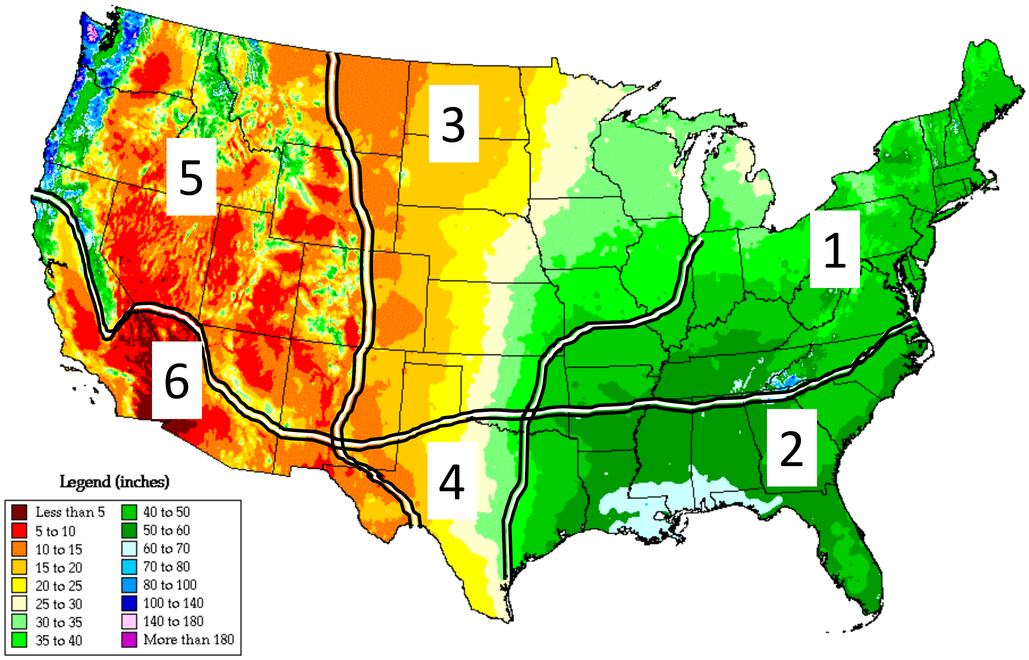
Figure 69. Slope–area plot. *Solid circles* represent average hillslope characteristics for a region in the Colorado Front Range. *Open circles* represent actual channel head locations as mapped in the field. *Vertical lines* signify transitions between regions denoted by inflections in the curve as interpreted in multiple studies of hillslope-channel process transitions. Regions are (*I*) hillslopes with soil creep, (*II*) unchanneled valleys, (*III*) transition zone, and (*IV*) alluvial channels. Note that some of the actual channel heads are well down into region IV and thus farther downslope than predicted using only remote topographic data (modified from Henkle et al. 2011, Fig. 8).



9 Regional Characteristics of Rivers and the OHWM

This section discusses the characteristics of rivers and the OHWM in eight regions of the United States (Figure 70). There are many ways in which the United States could be subdivided for this purpose; the eight designated here are designed to reflect important regional differences in climate, hydrology, geology, and topography without creating an unmanageably large number of categories. Channel-forming processes, including those associated with the relatively frequent floods that create the OHWM, act over different time scales in different rivers. Some of these differences are consistent between the geographic regions designated in this section, but other differences reflect the diversity of channel size, substrate, topography, precipitation patterns, and land use that occur within each of the eight regions. For example, a comparison of four mountainous, forested headwater basins in Oregon, North Carolina, New Hampshire, and Puerto Rico found that soil type exerted a particularly important control on stream flow response to fluctuations in daily precipitation; the catchment with shallow, coarse-textured soil (New Hampshire) was most responsive and the catchment with deep, highly weathered soil (North Carolina) was least responsive (Post and Jones 2001). On the other hand, tropical channels tend to have consistently higher peak discharge per unit drainage area (Wohl and Jaeger 2009) and relatively flashy flows (i.e., high magnitude, short duration) (Baker et al. 2004; O'Connor and Costa 2004) because of intense precipitation and rapid downslope transmission of runoff into stream channels (Niedzialek and Ogden 2005). The following discussion focuses on stream types typical of each region and on the most common and effective indicators of the OHWM within each region. In this context, it is worth noting that more information is available for some regions than for others. The regional differences described below highlight the need for regionalized technical resources for OHWM delineation.

Figure 70. Map showing six of the eight regions of the United States discussed in this document. (Alaska and Hawaii are regions seven and eight, respectively).



9.1 Basis for differentiating regions

The six regions within the continental United States are differentiated first on dominant native vegetation types. The eastern regions (1 and 2) are primarily forested although the forests includes substantial diversity of tree species. Forests in the eastern United States reflect relatively abundant precipitation (greater than approximately 16 cm, or 40 in.). The central regions (3 and 4) are primarily prairies. Woodlands are present along river courses and in other distinctive microclimates within the region, but the dominant native vegetation grades from tallgrass prairie in the eastern portion of these zones through mixed-grass prairie to shortgrass prairie along the western margins. The western regions (5 and 6) are predominantly mountainous areas with vegetation that grades from alpine tundra at the highest elevations down through subalpine and montane forest to grasslands or desert at the base of the mountains. The divisions between northern (1, 3, and 5) and southern (2, 4, and 6) regions are designed to reflect the importance of snowmelt to river discharge in the northern regions. The boundary between north and south approximately follows the line south of which mean annual snowfall is less than 0.7 m (2 ft).

Alaska and Hawaii each include substantial diversity in vegetation and precipitation. Alaskan vegetation varies from rainforest along the southeastern coast, where mean annual precipitation can exceed 5 m (167 in.), through boreal forest that receives less than 1 m (39 in.) of precipitation in the interior to tundra on the Brooks Range and Arctic coastal plain, parts of which receive less than 25 cm (10 in.) of rain (Figure 36C). Similarly, Hawaiian vegetation varies from tropical rainforest that can receive more than 6.5 m (256 in.) of rain on the windward side of the islands, to savannah that receives less than 1 m of rain on the leeward side of the islands (Figure 36B). Nonetheless, Alaska and Hawaii are each designated as one region.

9.2 Northeast

Rivers in region 1 have at least some flow resulting from snowmelt; and in some rivers, particularly those in the northern-most portion of this region, snowmelt dominates the flow regime (Huntington et al. 2009). Rainfall is also a very important component of runoff and can take several forms. Convective thunderstorms are especially important in smaller drainage basins. Deviations in the position of the polar front jet stream create migratory low-pressure systems that bring rain to the region (Huntington et al. 2009). Major storms can occur in any month of the year, typically in the form of nor'easters (cold-core, low-pressure systems) or, less commonly, tropical storms and hurricanes (Zielinski and Keim 2003).

In general, the relatively abundant precipitation in region 1 supports continuous vegetation cover, mostly forest, underlain by thick, well-developed soils with high infiltration capacity. Soils in the northeastern portion tend to be inceptisols (young soils with poorly developed horizons) whereas those in the northwestern portion are more likely to be alfisols (which have a clay-enriched B horizon and are characteristic of deciduous forests). Ultisols, well-weathered soils that are commonly rich in kaolinite clay, are common in the southern portion of region 1. A wide diversity of soils are present at finer spatial scales, reflecting the importance of local lithology, glacial history, and topography.

Although headwater streams can be ephemeral or intermittent, most medium to large rivers are perennial and have low intra- and interannual variability in discharge relative to rivers in other regions of the United States (Table 13; Figure 71). Abundant vegetation facilitates the use of botanical indicators of the OHWM and also facilitates the development of organic debris lines. Most rivers are straight or meandering although substantial variety can exist among the narrowly confined mountainous rivers in the northeastern portion of region 1, piedmont or coastal rivers along the eastern margin of the United States, and rivers along the margins of the Great Lakes. Region 1 includes some large karst terrains (Figure 55) that create the complicated surface–subsurface hydrologic paths discussed in section 7.8.

Table 13. Examples of average daily and annual discharge values for diverse river gaging stations within the United States. Relative intra-annual variability in discharge can be assessed by comparing regional average values of the coefficient of variation (CV) for daily discharge values. Relative interannual variability in discharge can be assessed by comparing regional average values of the CV for annual peak values.

Site	Drainage area (km^2)	Annual peak/ annual *Q*[1] ($m^3/s/km^2$)	Daily discharge (m^3/s)		Annual discharge (m^3/s)		Annual peak discharge (m^3/s)	
			Mean	CV[2]	Mean	CV	Mean	CV
Northeast		*15.43*[3]		*0.50*				*0.47*
Indian River near Indian Lake, NY	367	3.96	8.41	0.20	8.43	0.22	33.36	0.48
Delaware River near Barryville, NY	5611	15.07	92.14	0.47	92.10	0.31	1388.06	0.54
Little Delaware River near Delhi, NY	138	23.75	2.67	0.49	2.67	0.28	63.40	0.43
E Branch Delaware River at Fish’s Eddy, NY	2178	20.55	33.18	0.49	33.17	0.30	681.76	0.52
Rocky River at Berea, OH	742	29.73	8.55	0.63	8.54	0.34	253.89	0.41
Cuyahoga River at Old Portage, OH	1122	7.49	12.89	0.5	12.89	0.29	96.52	0.30
Scioto River at Higby, OH	14,253	9.89	138.0	0.59	138.08	0.32	1365.77	0.60
Hocking River at Athens, OH	2619	12.97	28.95	0.63	28.94	0.31	375.24	0.45
Southeast		*27.44*		*0.59*				*0.73*
Hatchet Creek below Rockford, AL	731	32.92	11.03	0.63	11.03	0.42	363.07	0.86
Little Tallapoosa River near Newell, AL	1128	12.80	15.72	0.57	15.71	0.39	201.05	0.47
Little Double Bridges Creek, Enterprise, AL	59	75.40	0.95	0.56	0.95	0.40	71.63	1.42
Alabama River at Claiborne, AL	59,647	4.77	865.61	0.56	864.76	0.37	4124.39	0.26
Cahaba River near Marion Junction, AL	4906	11.33	77.71	0.65	77.62	0.32	879.26	0.65
Northern prairies		*102.85*		*1.24*				*1.79*
Pembina River at Walhalla, ND	9306	16.15	8.14	1.41	8.25	1.00	133.25	1.13
Forest River near Fordville, ND	1267	38.95	1.31	1.41	1.33	0.87	51.80	1.45
Little Missouri River near Watford, ND	23,083	26.69	15.52	1.21	15.53	0.73	414.55	1.05
Green River near New Hradec, ND	422	77.73	0.40	1.53	0.40	0.87	31.09	0.86
Purgatoire River near Madrid, CO	1403	53.87	1.87	0.83	1.91	0.45	102.9	0.75
Arikaree River at Haigler, NE	4722	403.70	0.46	1.02	0.46	1.04	185.7	5.52
Southern prairies		*37.08*		*0.66*				*1.01*
Salt Fork Arkansas River at Tonkawa, OK	12,417	19.19	25.66	0.54	25.75	0.83	494.24	0.91
Salt Fork Red River near Elmer, OK	5508	46.90	5.47	0.88	5.37	0.81	251.83	1.24
Little River near Tecumseh, OK	1286	56.62	4.04	0.70	3.84	0.88	217.42	1.10
North Canadian River near Harrah, OK	38,264	17.95	13.38	0.49	13.36	0.63	239.85	0.72
Fourche Maline near Red Oak, OK	333	44.72	3.78	0.71	3.73	0.53	166.80	1.06

Site	Drainage area (km^2)	Annual peak/ annual *Q*[1] (m^3/s/km^2)	Daily discharge (m^3/s)		Annual discharge (m^3/s)		Annual peak discharge (m^3/s)	
			Mean	CV[2]	Mean	CV	Mean	CV
Northwest		11.21		0.64				0.70
Crab Creek near Moses Lake, WA (e side)[4]	6189	11.72	1.77	0.54	1.77	0.68	20.74	2.03
Mill Creek at Walla Walla, WA (e side)	266	14.16	2.25	0.88	2.25	0.38	31.85	0.56
Tucannon River near Starbuck, WA (e side)	1197	10.22	4.82	0.51	4.82	0.35	49.26	0.96
Crab Creek near Beverly, WA (e side)	24,556	1.68	5.58	0.16	5.62	0.28	9.45	0.34
Hoh River near Forks, WA (w side)	703	13.56	71.53	0.42	71.42	0.18	968.16	0.36
Snohomish River near Monroe, WA (w side)	4269	6.88	269.46	0.40	270.14	0.20	1857.51	0.39
Hoko River near Sekiu, WA (w side)	150	21.12	11.01	0.80	11.11	0.21	234.60	0.46
Big Thompson River in Moraine Park, CO	111	10.38	1.56	1.39	1.59	0.32	16.5	0.49
Southwest		*60.01*		*1.14*				*13.85*
Whitewater Draw near Douglas, AZ	2842	175.00	0.24	2.00	0.24	0.82	42.0	0.80
E Fork White River near Fort Apache, AZ	108	10.64	0.93	0.75	0.94	0.48	10.0	1.22
Muddy River near Glendale, NV	8333	41.85	1.19	0.25	1.19	0.20	49.8	51.84
Lamoille Creek near Lamoille, NV	69	12.67	1.24	1.55	1.25	0.34	15.7	1.53
Alaska		*8.72*		*1.02*				*0.41*
Matanuska River at Palmer, AK	5750	6.86	111.25	1.12	109.97	0.15	754.18	0.42
Stikine River near Wrangell, AK	55,333	3.86	1565.28	0.86	1565.86	0.12	6041.10	0.22
Ship Creek near Anchorage, AK	249	6.21	4.10	0.90	4.11	0.22	25.53	0.37
Salcha River near Salchaket, AK (interior)[5]	6028	11.93	45.05	0.93	45.11	0.28	538.31	0.66
Wulik River near Kivalina, AK (n slope)	1958	18.57	27.83	1.30	27.85	0.32	517.30	0.47
Susitna River at Gold Creek, AK	17,111	4.91	275.07	0.98	275.43	0.13	1351.03	0.33
Hawaii		*77.92*		*0.48*				*0.56*
Wailuku River at Piihonua, HI	611	76.62	7.29	0.46	7.35	0.41	563.19	0.68
Honolii Stream near Papaikou, HI	33	79.22	3.42	0.50	3.43	0.33	271.71	0.45

[1] Ratio of average annual peak discharge to average annual discharge

[2] CV is coefficient of variation (= standard deviation/mean).

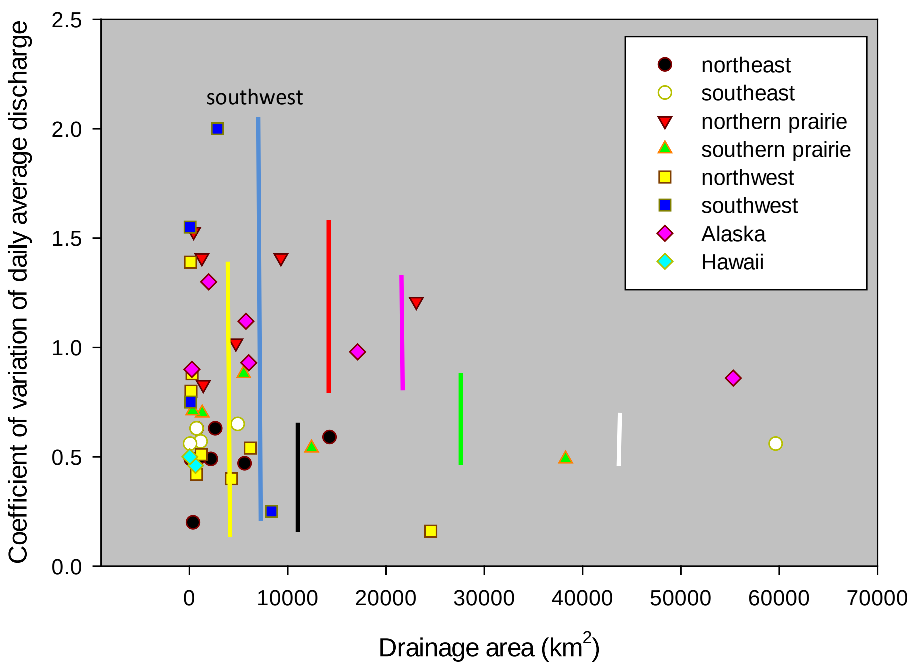
[3] Italicized values are averages for that region.

[4] Rivers on the eastern and western side of the Cascade Range in Washington are distinguished here because of the substantial difference in climate between the semiarid eastern side and the humid temperate western side.

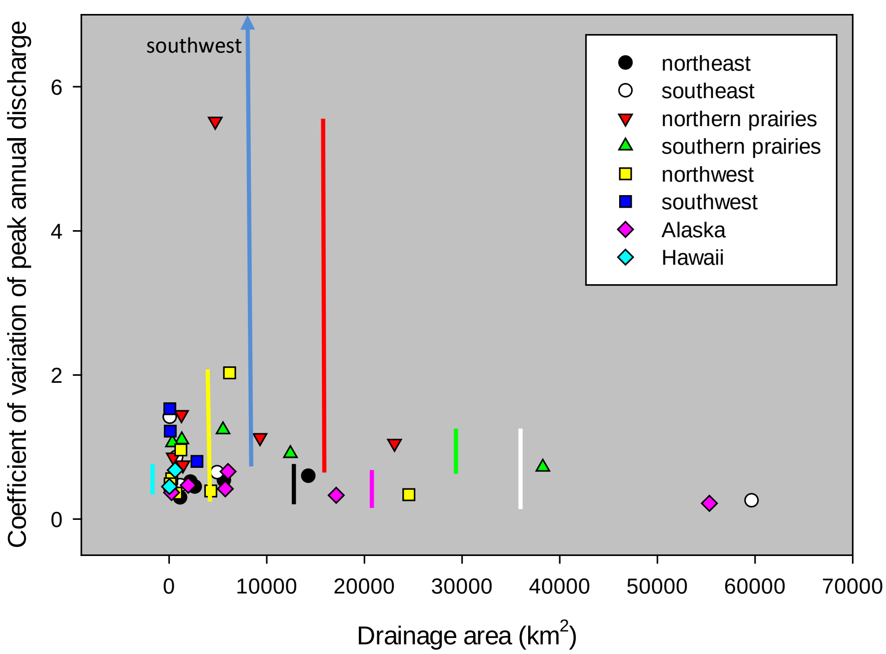
[5] Rivers in the interior of Alaska and on the northern slope are distinguished from those of the southern portion of Alaska.

Figure 71. Graphical illustration of regional differences in coefficient of variation (*CV*) for (*A*) average daily discharge and (*B*) peak annual discharge. The colored vertical bars represent the range of CV values for each region. Rivers of the southwestern United States have by far the largest range and the greatest values whereas rivers of the northeastern and southeastern regions have low average values and a relatively small range within each region. The highest value for the southwest in (*B*) extends well beyond the maximum value on the y-axis; the highest value was not included to make it easier to discern relative variations among the other regions.

A



B



9.3 Southeast and Caribbean

Rivers in region 2 receive only minimal snowmelt runoff and are dominated by diverse types of rainfall runoff. Rainfall is abundant because of nearby moisture sources such as the Gulf of Mexico and the warm waters of the Atlantic Gulf Stream. Rainfall can occur at diverse spatial scales and intensities, from localized convective storms to low-pressure zones migrating across the entire region. Dissipating tropical storms that cross over the region during late summer and autumn can exert a particularly important influence on rivers in region 2 by creating widespread, intense precipitation that triggers landslides, debris flows, associated inputs of sediment and large wood to rivers, and substantial runoff (Phillips and Park 2009).

Abundant precipitation (typically 1 to 1.8 m, or 40 to 70 in., per year) and limited duration of freezing temperatures that limit soil microbial activity result in primarily ultisols in region 2. The wet climate supports continuous vegetation cover, which is mostly forest. As in region 1, headwaters can be ephemeral or intermittent; but most medium to large rivers are perennial with straight or meandering planform. As in region 1, however, rivers of the Appalachians can be quite different from those of the piedmont and Atlantic coastal plain, the Gulf coastal plain, or the karst terrains of Florida. Region 2 is distinguished by having extensive areas underlain by carbonate rocks and associated, well-developed karst (Figure 57). Abundant vegetation facilitates the use of botanical indicators of the OHWM, and also facilitates development of organic debris lines.

Rivers of the Caribbean—primarily those in Puerto Rico and the U.S. Virgin Islands, in the context of this document—tend to flow from mountainous headwaters across narrow coastal plains to the sea. Diverse lithologies are present, including extensive karst along the northern third of the island. Landslides are common in mountainous areas (Larsen et al. 1999). Deeply weathered soils are rich in clay (Pike et al. 2010).

The humid subtropical maritime climate of the Caribbean is influenced by northeasterly trade winds and local orographic effects with steep elevational gradients in precipitation. Rainfall in Puerto Rico, for example, varies from about 1.5 m (49 in.) per year at the coast to more than 4.5 m (177 in.) at higher elevations (García-Martinó et al. 1996). Rainfall occurs on most days; but hurricanes and tropical storms, which are common from August through October, commonly bring daily rainfall of 20 cm (8 in.) or more (Heartsill-Scalley et al. 2007). Rainfall runoff is conveyed quickly downslope via macropores and saturation overland flow (Schellekens et al. 2004). Rivers tend to be dominated by floods (Gupta 1988; Ahmad et al. 1993). Flood peak discharge can be 1000 times greater than base flow (unit discharge of 0.02 $m^3/s/km^2$) (Pike et al. 2010). Hydrographs are extremely flashy with flood peaks typically lasting less than an hour and rivers returning to base flow within 24 hours of large events (Pike et al. 2010). Relationships between flood frequency and vegetation zoning with elevation above the channel are consistent and well documented (Pike and Scatena 2010).

Rivers of the coastal plain have undergone substantial changes since circa 1830 when agricultural development increased runoff by 50% and increased sediment supply by more than an order of magnitude (Clark and Wilcock 2000). Urbanization of industrial lands since 1950 has maintained elevated runoff but reduced sediment inputs to channels, causing channel erosion in the upstream reaches and a downstream decrease in channel cross-sectional area because sediment released during land clearance continues to be stored in downstream reaches of channels (Clark and Wilcock 2000).

9.4 Northern prairies

Rivers in region 3 are prairie rivers although a narrow riparian forest can be present along the margins of the active channel and across the floodplain. Trees are limited in region 3 because of the relatively dry climate; mean annual precipitation ranges from approximately 1 m (40 in.) in the east to only 25 cm (10 in.) in the western part of region 3. Snowmelt is important in the northern and central portions of the region, and rivers throughout the region that head in the Rocky Mountains are dominated by snowmelt runoff. Summer convective storms are likely to create the ordinary and extraordinary HWMs in smaller rivers, which are commonly ephemeral or intermittent. River flow regimes exhibit greater intra- and interannual variability from east to west within region 3. Soils of region 3 vary from thick, well-developed mollisols with high infiltration capacity in the eastern portion of the region to thinner, typically sandy entisols and aridisols in the western portion.

The minimal topographic relief in region 3 can result in diffuse channel networks in which individual channel segments are swales with multiple, subparallel flow paths and poorly defined bed and banks. River planforms can be straight, meandering, or braided, with braided rivers more common in the western portion of the region. Prairie potholes, depressional wetlands that are primarily freshwater marshes, occur in the northern portion of region 3; and playas (shallow, sometimes ephemeral lakes or wetlands) occur in the western half of the central and southern portions of the region.

Vegetative indicators of the OHWM, including fine organic debris, are likely to be particularly useful in region 3 in channels with herbaceous vegetation growing in the channel. In unvegetated channels, geomorphic indicators can be useful in constraining the elevation of the OHWM. The lack of elevation-related precipitation gradients can also enhance the accuracy of regional extrapolation of hydrologic indicators based on drainage area–discharge relations although flow regulation and extensive modification of land cover and channel geometry (primarily via channelization) can limit the usefulness of this extrapolation.

9.5 Southern prairies

As in region 3, rivers of region 4 occupy grasslands although narrow riparian forests are present along the margins of the active channel on some rivers. Mean annual precipitation is only 25 to 75 cm (10 to 30 in.) and results primarily from rainfall. Large rivers that head in the Rocky Mountains and flow into the Missouri and Mississippi Rivers are perennial, but most other rivers are ephemeral or intermittent. Ephemeral rivers, in particular, can have very flashy hydrographs with runoff resulting from convective thunderstorms. Although thicker mollisols can be present in the eastern portion of region 4, thin entisols and aridisols with limited infiltration capacity characterize much of the region.

Rivers can be straight, meandering, braided, or anastomosing, with braided rivers more common in the western portions of region 4. Small- to medium-sized rivers commonly undergo repeated cycles of incision and aggradation over multiple decades to centuries. Sometimes incision or aggradation can be triggered by land uses such as groundwater withdrawal or overgrazing, but incision–aggradation cycles have characterized rivers of this region throughout the past several thousand years of geologic history (e.g., Hall 1990). Playas occur in region 4, and relatively small karst terrains are present in parts of New Mexico and Texas.

As in region 3, vegetative indicators of the OHWM, including fine organic debris, are likely to be particularly useful, as are geomorphic indicators.

The lack of elevation-related precipitation gradients facilitates regional extrapolation of drainage area–discharge relations, subject to uncertainties associated with changes in land cover and flow regulation.

9.6 Northwest

Region 5 encompasses enormous climatic and topographic diversity, from the temperate rainforest of the northwestern coast and mountains to the interior deserts. The commonality is high topographic relief and the associated local variations in precipitation, temperature, vegetation, and river flow. Except for a relatively narrow portion of western Washington, Oregon, and northern California, region 5 has a predominantly arid or semiarid climate. Mean annual precipitation exceeds 4 m (157 in.) in the highest northwestern mountains, but much of the region receives less than 50 cm (20 in.) of precipitation each year.

Soils, vegetation, and river geometry and flow regime all vary greatly within region 5. Mountainous catchments are typically forested with primarily conifer species; and these forests historically introduced abundant wood into rivers, creating many anastomosing channels (Wohl 2011; Collins et al. 2012). Mountainous rivers are also likely to be dominated by a strongly seasonal snowmelt runoff peak. Smaller channels can be ephemeral or intermittent in any part of region 5, and even large channels are likely to be ephemeral or intermittent in the drier portions of the region. Rivers in the mountainous portions of region 5 can be straight, meandering, braided, or anastomosing.

Rivers flowing across the lowlands surrounding the numerous mountain ranges of region 5 can be perennial if they originate in the mountains and are fed by snowmelt but are otherwise likely to be ephemeral or intermittent. Braided rivers are especially common in the lowlands although any type of channel morphology can be present. As in region 4, smaller rivers in the dry portions of region 5 have undergone repeated cycles of incision and aggradation throughout the past few thousand years.

Region 5 includes three large karst terrains (Figure 57). Lichvar and McColley (2008) thoroughly discuss the OHWM in region 5. Diverse forms of geomorphic and vegetative OHWM indicators are particularly useful in region 5.

9.7 Southwest

Rivers of region 6, the desert southwest, are now likely to be ephemeral or intermittent rivers unless they are supplied by imported water. This was not necessarily the case historically; many of the desert rivers were perennial during the nineteenth century (Webb et al. 2014), but land uses, including groundwater withdrawal, have substantially altered flow regime in this region. Very large rivers such as the Colorado River may head in mountainous regions supplied by snowmelt, but flow in most rivers of region 6 is dominated by rainfall runoff. Convective thunderstorms produce flash floods and monsoonal rains, or dissipating tropical storms from Baja California can produce more widespread and sustained rainfall that creates extraordinary floods on medium to large rivers in region 6 (Merritt and Wohl 2003).

Limited rainfall (mostly less than 12 to 60 cm, or 5 to 25 in.) results in discontinuous vegetation cover that varies from scrublands and grasslands to cacti although narrow riparian forests can be present. Soils are mostly thin, poorly developed aridisols with limited infiltration capacity. Although any channel form can occur, braided rivers are particularly characteristic of region 6. Rivers of all sizes are also prone to undergo cycles of alternating incision and aggradation (Graf 1988; Webb et al. 2014). High intra- and interannual flow variability (Table 13; Figure 71) and limited riparian vegetation create channels highly prone to change during extraordinary floods and conditions under which extraordinary HWMs can persist for years to decades. For the most part, karst terrains are not present in this region.

Lichvar and Wakeley (2004) and Lichvar and McColley (2008) provide thorough overviews of the OHWM in region 6. Diverse geomorphic and vegetative indicators can be used to constrain the elevation of the OHWM in this region, but the dry climate means that HWMs from extraordinary floods are particularly likely to persist and to complicate efforts to identify an OHWM.

9.8 Alaska

Region 7, which is the entire state of Alaska, encompasses an enormous area that covers a large range of latitudes and longitudes and the associated diversity of climate, hydrology, and river geometry. The region can be generally subdivided into three bands that trend more or less east–west although each band is sinuous. The southern band parallels the southern coastline and includes areas that receive from approximately 60 cm (24 in.) to less than 5 m (197 in.) of mean annual precipitation (Figure 37). This region is characterized by dense coniferous forest. Along the south-eastern portion of the coast, this rainforest is similar to the forest of the Pacific Northwest coastal areas. The terrain is primarily mountainous, and the forest is underlain by inceptisols. Snowmelt creates a seasonal runoff signal although rainfall throughout the remainder of the year also contributes to river flow. Rivers flowing from glaciers are likely to be braided; other rivers in this portion of region 7 are likely to be straight or meandering.

The middle band of region 7 includes areas that receive approximately 35 to 60 cm (14 to 24 in.) of mean annual precipitation (Figure 37). Much of this area is covered by boreal forest dominated by white and black spruce, which are able to survive where permafrost is present. Permafrost, or permanently frozen ground, is covered by an active layer that can be from a few millimeters to more than a meter thick. The active layer thaws each year, but the presence of perennially frozen ground below the active layer limits infiltration capacity. Consequently, even areas that receive relatively little precipitation can have abundant wetlands and saturated soil. Many of the soils in the middle band of region 7 are inceptisols. River geometry can take any form. The Yukon River, for example, is the major river of the region, draining west from headwaters in Canada. The central portion of the Yukon River includes braided, meandering, and anastomosing portions (Figure 72).

The northern band and a central-eastern portion of Alaska receive less than 35 cm (14 in.) of mean annual precipitation (Figure 36) although, as noted above, the presence of permafrost limits infiltration capacity and supports abundant wetlands (Figure 73). Vegetation in this portion of region 7 is primarily tundra, and soils are mostly gelisols. Rivers can have any geometry, but braided planforms are particularly common.

Figure 72. Examples of different channel planforms along the Yukon Flats portion of the Yukon River in central Alaska. (Images from Google Earth, Landsat, 4/2013 imagery date.)

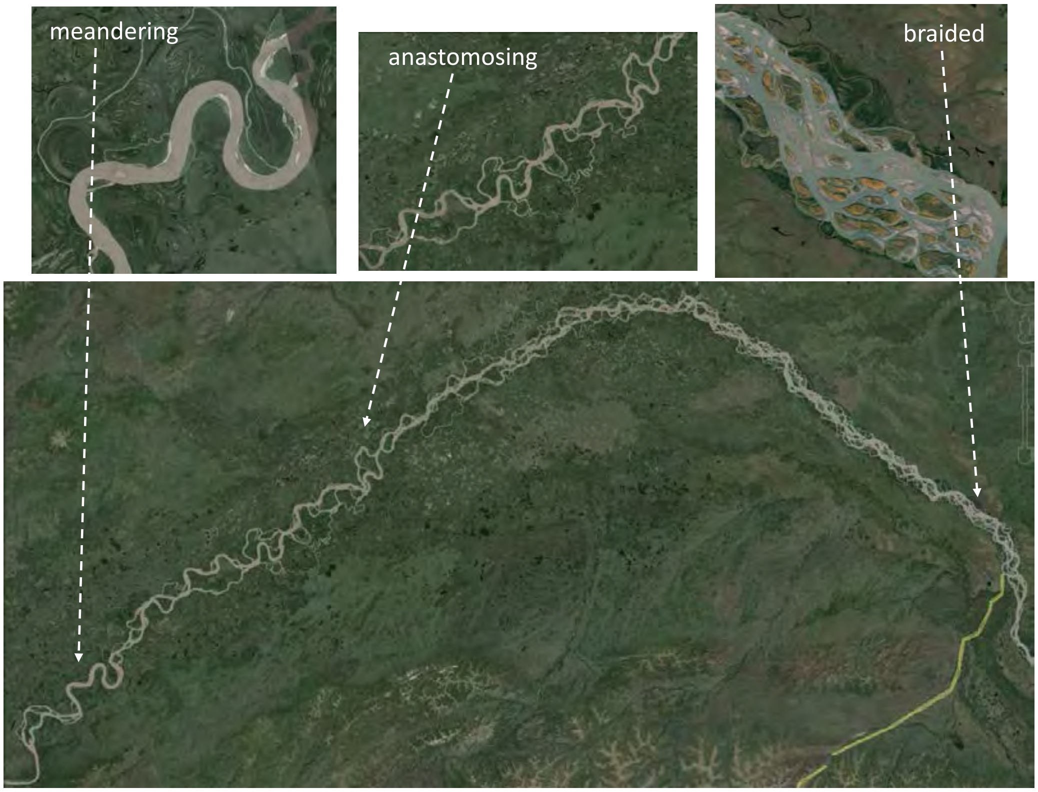


Figure 73. Abundant wetlands in the Alaskan interior, despite relatively low annual precipitation, reflect the presence of permafrost, which impedes infiltration and drainage.

Two characteristics that are important in the context of the OHWM and that many rivers throughout Alaska share are the influence of ice dynamics and the effects of warming climate on permafrost. Seasonal ice cover characterizes rivers throughout Alaska. The formation and breakup of this ice can create HWMs that do not necessarily correspond to high river discharge. The hydraulic resistance associated with an ice cover elevates water levels in a channel (Prowse and Beltaos 2002), an effect that is greatest when the ice cover is most hydraulically rough, such as during freeze-over and breakup. Breakup is most important in this context; breakup frequently establishes the annual maximum water levels even though maximum discharge is more likely to result from snowmelt or rainfall later in the melt season (Prowse and Ferrick 2002). Water stored in river ice can be released during breakup, accounting for nearly 20% of the spring peak flow (Prowse and Carter 2002); and large chunks of ice mobilized during breakup can create jams and abrade the river banks and riparian vegetation at elevations well above the actual water surface (Gottesfeld and Johnson Gottesfeld 1990; Goulding et al. 2009; Ettema and Kempema 2012). Although breakup used to be a dramatic and relatively predictable annual event in many rivers of central Alaska, warming climate has resulted in thinner ice that breaks up earlier each season and is less likely to create an elevated water stage (Goulding et al. 2009; de Rham et al. 2008). During some years, river ice now simply disappears, without actually breaking up into chunks that can cause ice jams.

Warming climate is resulting in well-documented melting of permafrost. This takes two forms: a northward retreat of the southern extent of permafrost and thinning of permafrost from the top down, which effectively increases the depth of the active layer. Melting permafrost is changing the balance between infiltration and runoff and surface and subsurface flow paths into rivers and is increasing hillslope instability and river bank erosion (Dyke et al. 1997).

Diverse geomorphic and vegetative indicators are useful in constraining the elevation of the OHWM in rivers of region 7. The wet climate of the southern portion of Alaska is likely to result in more rapid modification of geomorphic and vegetative indicators following a high flow whereas the drier central and northern portions of the region can retain extraordinary HWMs for many years.

9.9 Hawaii

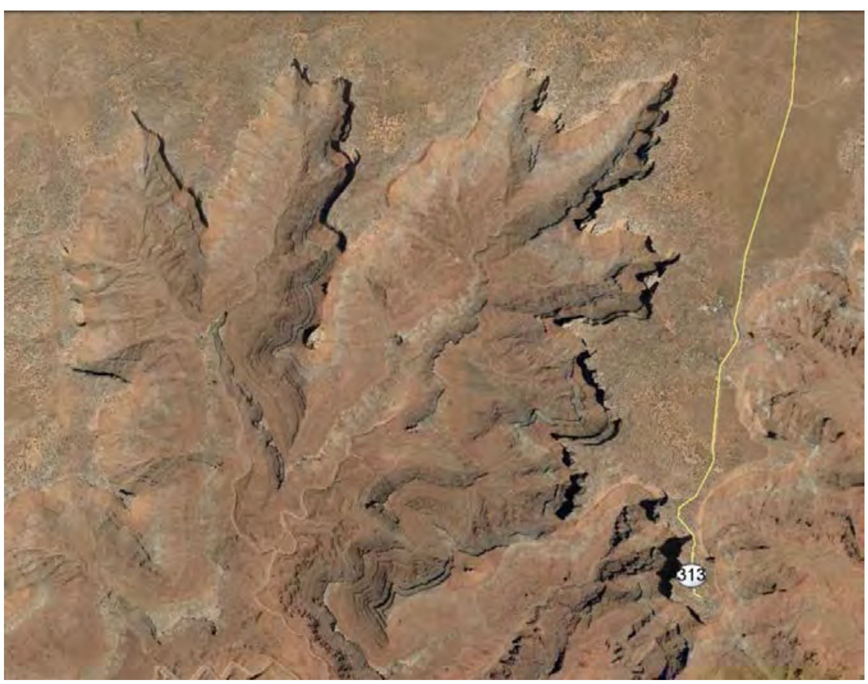
Region 8 consists of the Hawaiian Islands. The islands are geologically young terrain with continuing production of new bedrock through volcanic eruptions. Among the key features of rivers in region 8 with respect to the OHWM are (i) the marked precipitation gradients from the windward to the leeward side of each island (Figure 37B); (ii) high intensity rainfall that is typically of brief duration but can be prolonged during the major storms that occur during October to March; (iii) the occurrence of piping and sapping in soils and bedrock; and (iv) the predominantly steep terrain and stepped topography of the islands. The strong spatial gradient in mean annual precipitation across each island limits regionalization of drainage area–discharge relations. Hawaii has a rainy season during October to March although rain can fall at any time during the year. Major storms can be caused by passage of a cold front, a low-pressure system (Kona storms), a hurricane, or upper-atmosphere low-pressure systems (lows and troughs). Hawaiian soils are diverse with ten of the twelve soil orders present on the islands but tend to be rich in clays that can limit infiltration. Combined with intense rainfall and steep terrain, this leads to flashy streams in which discharge and water level can change dramatically over a few hours (Oki and Brasher 2003).

Piping and sapping refer to preferential flow in the subsurface. Piping occurs above the water table, and sapping occurs below the water table. In each case, if sufficient subsurface flow is concentrated in pipes, macropores, or along bedding planes or other bedrock heterogeneities, the removal of mass in the subsurface can eventually cause the overlying material to collapse, creating a channel with surface flow. In Hawaii, much of the piping and sapping occurs between layered volcanic rocks deposited by successive eruptions. Piping and sapping channels have a characteristic shape: an amphitheater-headed channel with a nearly vertical headwall, a relatively consistent valley width downstream from the headwall, and a gentle downstream gradient in the surface channel (Figure 74). The upstream end of a sapping channel can also be supplied with relatively consistent discharge by a spring.

Figure 74. (*A*) View down a sapping channel on Kohala Mountain in Hawaii. The abrupt head of the channel is indicated by the foreground, which drops precipitously to the surface channel at the bottom of the valley. (*B*) The characteristic “amphitheater head” of sapping channels is particularly well illustrated by this aerial view of Dead Horse Point State Park in Utah. (Image from Google Earth, 7/2015 imagery date.)

A

B



The steep terrain and stepped topography of the Hawaiian Islands result from young volcanic deposits that have not been highly modified by weathering and erosion. Rivers draining the islands tend to be straight and narrowly confined between valley walls and longitudinally stepped. Drainage areas are small, but rivers flowing from highlands that receive more than 5 m (197 in.) of rainfall each year can have substantial flow despite the small drainage area.

Geomorphic and vegetative HWMs are more likely to persist in the drier areas of the Hawaiian Islands whereas rapid weathering and vegetative regrowth can obscure HWMs in the wetter portions of the islands. Consequently, it may be easier to distinguish an *ordinary* HWM in the wetter areas.

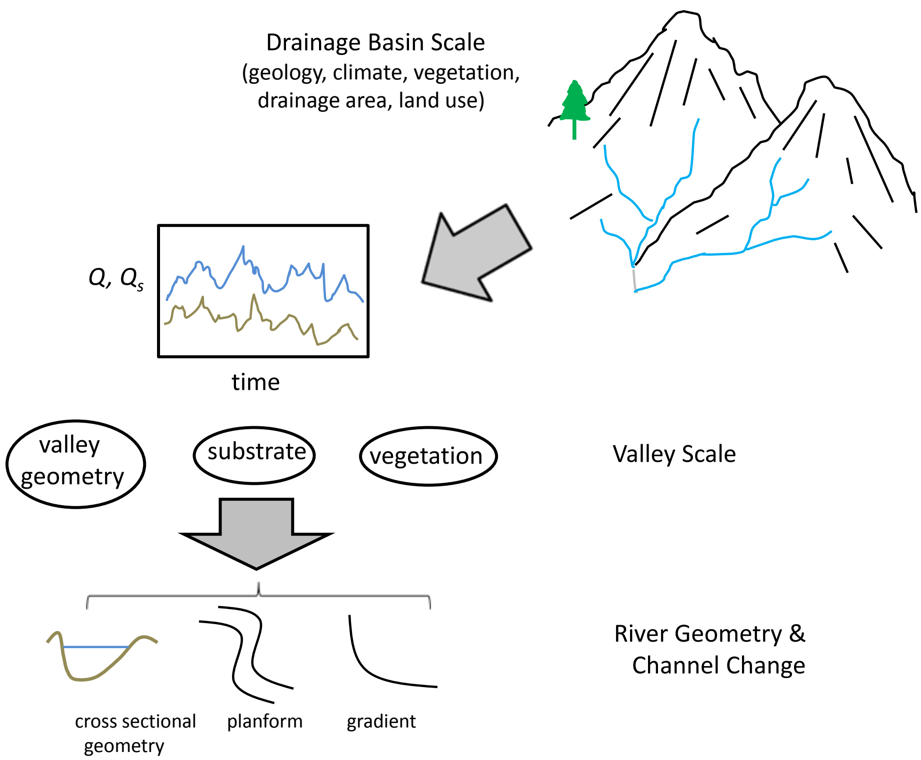
10 Concluding Remarks

Rivers of the United States have a great diversity in terms of climate and precipitation types and upland flow paths that generate river flow; variability in river flow within an average year and between years; channel geometry; erosional resistance of the channel boundaries and response to flows of differing magnitude; time interval required for a channel to return to its pre-flood configuration following a large flood; and history of human-induced alterations of the drainage basin, flow regime, and channel geometry. Consequently, regionally focused guidelines that recognize distinctive hydroclimatic and geomorphic characteristics are most useful for delineating the OHWM at any particular river site and for delineating the upstream extent of each channel.

In many rivers, uncertainty as to the recurrence interval of the flows that created individual HWMs make it most effective to delineate the OHWM by constraining its elevation based on geomorphic and vegetative indicators that typically occur above, at, and below the ordinary high water level. The lowest potential boundary of the OHWM in a given river is within the active channel, especially in deeply incised systems. The highest potential upper boundary of the OHWM may be on the valley flat or floodplain outside of the active channel in locations where these features are inundated in more years than not.

The OHWM is transitory as a result of natural channel changes and human-induced alterations. In addition, ongoing climate change is creating a scenario in some regions of the United States in which previously extraordinary floods are occurring more frequently (i.e., the recurrence interval for extreme floods is becoming shorter). Because of the numerous factors that interact to influence the creation and preservation of the OHWM (Figure 75), the OHWM is site-specific and typically is most effectively delineated by using field indicators at each river segment.

Figure 75. Schematic illustration of the factors that influence river geometry and channel adjustment. At the scale of the drainage basin, regional factors such as geology and climate influence water and sediment inputs to the river network. Discharges of water (*Q*) and sediment (*Q_s*) interact with valley-scale controls of valley geometry, substrate characteristics of the channel and floodplain (i.e., grain size—such as sand versus bedrock), and riparian vegetation to govern cross-sectional geometry, planform, and gradient of a river reach and changes in these reach-scale parameters through time and space.



Glossary

Active channel: a portion of the valley bottom that can be distinguished based on the three primary criteria of (i) channels defined by erosional and depositional forms created by river processes, (ii) the upper elevation limit at which water is contained within a channel, and (iii) portions of a channel without mature woody vegetation

Alluvium: sediment deposited by water flowing within a channel

Anastomosing channel segment: multiple secondary channels that branch and rejoin downstream, with vegetated, relatively stable areas above the elevation of the channel banks separating individual secondary channels

Bank: the side of an active channel, typically associated with a steeper side gradient than the adjacent channel bed, floodplain, or valley bottom

Bankfull channel: the portion of the channel below the top of the banks, with *top of banks* defined by a break in slope between relatively high-angle banks and relatively flat overbank portions of the valley bottom

Bankfull discharge: the flow that fills the channel to the top of the river banks

Base level: the lowest point to which a river will erode; sea level is the ultimate base level, but local base levels can occur where a river enters a lake or another, larger river

Bed: the base of the active channel, distinguished as having a lower average side gradient than the adjacent banks

Bedform: a deposit on the river bed that is formed by fluvial processes and typically repeated downstream (e.g., pool, riffle, point bar, alternate bar, ripple, or dune)

Bed material: sediment in transport and found in appreciable quantities in the streambed; typically includes bedload that travels in contact with the bed by rolling, sliding, and bouncing and a suspended load of sand-size or coarser

Braided-channel segment: multiple secondary channels that branch and rejoin downstream, typically with unvegetated sections of floodplain between secondary channels; individual secondary channels can move laterally during a single flood

Channel avulsion: formation of a new channel that is commonly parallel or subparallel to the existing channel(s)

Channel head: the upstream boundary of concentrated water flow and sediment transport on a distinct bed and between definable banks that are longitudinally continuous downstream

Channel maintenance flow: components of a river's flow regime necessary to maintain specific physical characteristics such as sediment transport or channel cross-sectional area

Channel migration zone: the width of the valley bottom across which main and secondary channels can migrate and have migrated under the contemporary flow regime

Channel stability: the ability of a channel to resist changes in cross-sectional geometry, planform, or gradient during a specified time interval; a stable channel experiences relatively little net erosion or deposition during a large flood

Channel substrate: the sediment or bedrock in which a river channel is formed (i.e., the material that composes the bed and banks)

Colluvium: sediment deposited by processes other than water flowing within a channel (e.g., rockfall, debris flow, landslide, or sheetwash)

Contributing area: the portion of a drainage area contributing runoff to a river segment during any particular precipitation event

Contributing basin: synonymous with contributing area

Debris flow: a slurry of water and sediment that is typically contained within a channel but has much higher sediment concentration and viscosity than river flow

Dominant discharge: a hypothetical single flow magnitude that, if sustained, will maintain consistent channel geometry; this has been quantified as the flow that (i) transports the greatest proportion of suspended sediment when averaged over some time interval that is typically greater than a year, (ii) transports the greatest proportion of bedload or total sediment when averaged over some time interval greater than a year, or (iii) is most responsible for shaping channel geometry; but these criteria are not necessarily met by a single flow

Drainage area: the surface area that drains to a particular reference point on a river

Drainage basin: synonymous with drainage area

Effective discharge: the discharge that transports the largest amount of sediment over time; in other words, effective discharge is synonymous with the first and second definitions of dominant discharge above

Environmental flow: an entire annual hydrograph, or specific portions of an annual hydrograph (e.g., peak flow), interpreted to maintain specific aspects of a river; typically, environmental flow recommendations specify magnitude, frequency, timing, duration, and rate of change in flow

Ephemeral river: flows only during and soon after precipitation inputs; an ephemeral river has no groundwater inputs or base flow

Floodplain: a relatively flat sedimentary surface adjacent to the active channel that is built by river processes and inundated frequently

Flow duration curve: a plot that equates discharge magnitude to the percent of time that the discharge is equaled or exceeded at a particular geographic point along a river

Flow regulation: dams and diversions that change the characteristics of water and sediment fluxes within a river

Hydrograph: a plot of river discharge through time, typically either during a flood or over a longer time interval such as a year

Hyporheic zone: the portion of unconfined, near-stream aquifers where river water is present; this zone is a flow-through subsurface region in which flow paths originate and terminate at the river

Instream flow: the minimum discharge needed to preserve a specific aspect of a river (e.g., pool volume, water temperature, or longitudinal connectivity)

Intermittent river: a river that flows continuously only at certain times of the year when the water table intersects the surface along the river course

Mean annual flow: average volume of flow for an individual year of a multi-year period of interest

Nonstationarity: variables, such as flow, for which the mean changes through time as a result of changes in climate, land use, or other factors, do not exhibit stationarity (see definition below) and therefore exhibit nonstationarity

1.5-year flow: a discharge magnitude that recurs, on average over the period of record, once every 1.5 years (an analogous definition applies to a 20-year flow, 50-year flow, etc.)

Ordinary high water mark: defined by Federal Regulations as the line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas

Orographic precipitation: precipitation produced as moist air lifts and moves over a mountain range; moisture in the air condenses as the air rises and cools

Perennial river: a river that flows at all times and along the entire length of the river except during periods of extreme drought

Piping: preferential subsurface flow that occurs above the water table in the unsaturated zone

Resilience: the tendency of a channel to return to its pre-flood configuration following a large flood; a resilient channel returns to its pre-flood configuration relatively quickly

Riparian zone: adjacent to rivers, lands that are transitional between terrestrial and aquatic ecosystems through which surface and subsurface hydrology connects river waters with their adjacent wetlands, non-wetland waters, or uplands

River corridor: the portion of any landscape that has been created by river erosion and deposition through time and that remains connected to the contemporary river at least during ordinary floods

Sapping: preferential subsurface flow that occurs below the water table in the saturated zone

Secondary channel: a subsidiary channel that branches from the main channel and trends parallel or subparallel to the main channel before rejoining it downstream

Stationarity: the assumption that natural systems fluctuate within an unchanging envelope of variability; in hydrology, expressed as an unchanging mean of hydrological parameters, such as mean annual flow or peak annual flow; stationarity implies that any variable has a time-invariant probability density function whose properties can be estimated from systematic measurements of discharge

Stream head: the upstream-most point in a river in which perennial flow occurs

Stream order: a numerical value assigned to a river segment based on the number and size of upstream tributaries; in the most commonly used stream-order system, a first-order river has no tributaries, a second-order river is present downstream from the junction of two first-order rivers, and two rivers of equal magnitude must join to form the next stream order

Thalweg: a line defined by the downstream succession of points of deepest flow within a river channel

Uplands: any portion of a drainage basin outside of the river corridor

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14. ABSTRACT
For more than 100 years, the ordinary high water mark (OHWM) has been used to define water boundaries in a number of contexts in the United States. This Special Report summarizes the scientific literature pertaining to the indicators used to identify the OHWM in fluvial systems, building on more than a decade of research and publications related to the OHWM in the ongoing process to implement the Clean Water Act and the Rivers and Harbors Act of 1899. This report does not change or redefine the indicators used to identify the OHWM, nor is it a manual for how to delineate the OHWM.

This report first reviews established concepts in river science that relate to the OHWM then reviews various sources of information that can be used to delineate the OHWM, discusses geographic variations in OHWM indicators among river segments, reviews human activities that can affect the OHWM, and finally presents examples of the OHWM in diverse channel types and regions.

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