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Best Practices for Managing Bank Erosion within the National Park Service and National Wild and Scenic River System



Photos in a clockwise direction starting from the top: Freemont River (CARE), Poor Creek (PETE), Nissitissit River (Wild and Scenic River in New Hampshire), West Union Creek (GOGA).

NPS

Best practices for managing bank erosion within the National Park Service and National Wild and Scenic River System

Science Report NPS/SR—2025/234

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Abstract

Riverbank erosion is a natural process that occurs as rivers adjust to disturbance events and to changes in water and sediment delivery over time. The resulting lateral movement of river channels is fundamental to building complex, dynamic, and resilient landscapes. In this sense, bank erosion is crucial to creating healthy rivers and should be preserved whenever possible. However, river managers may deem protection from bank erosion necessary if bank retreat threatens infrastructure, developed land, or other valuable natural and cultural resources. The National Park Service manages over 220,000 miles of rivers, approximately 3,750 of which are part of the National Wild and Scenic River System, encompassing various climatic, geological, watershed, and land use settings. These rivers have unique protections granted under National Park Service policies and the Wild and Scenic River Act, which require any action taken to mitigate bank erosion must minimize impacts to natural processes and river health. This document provides river managers with guidance and tools to ensure that bank erosion management aligns with the protections granted to Wild and Scenic Rivers and rivers managed by the National Park Service. River managers should reference this document during the project conceptual design phase to steer bank erosion management practices toward techniques that maintain the ecological and geomorphic functions of rivers. When evaluating a bank erosion issue, managers are encouraged to determine if erosion can be allowed to continue unimpeded or if offsite measures can be undertaken to slow the rate of bank retreat. A variety of surface treatments and flow deflection treatments are described for situations in which on-site bank protection is deemed necessary. Deformable treatments and those using organic materials, such as live vegetation or logs, are generally favored over those using inert materials, such as concrete and rock riprap.

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Introduction

Riverbank erosion is a natural and common process that allows rivers to adjust to short- and long-term changes in streamflow and sediment contributed by the watershed. Although the amount of water and sediment delivered to a river varies, rivers are remarkably resilient to short-term fluctuations in watershed conditions when allowed the freedom and space to adjust and laterally shift. In some settings, large floods temporarily widen channels, and bank erosion might seem quite extensive after the flood, but the channel narrows during subsequent years when more common flows and smaller floods occur. Channels with armored banks, on the other hand, cannot adjust their width, making them prone to secondary effects such as changes in geometry (e.g., depth), gradient, or channel pattern (e.g., shift from meandering to braided) (Shields et al. 1995). Providing rivers with space to migrate creates resilient river and floodplain environments capable of regulating changes in channel morphology while sustaining complex aquatic and riparian habitats. In this sense, riverbank erosion is essential for maintaining geomorphic stability and sustaining riverine ecosystems and their dependent biota.

Riverbanks are transitional boundaries between the channel and overbank areas, and they are critical to fundamental ecological processes (Florsheim et al. 2008). Sediment and wood derived from actively eroding banks build in-channel habitats, such as the sandbars on the Platte River used by migrating whooping and sandhill cranes (Kinzel 2009). In other settings, bank swallows and kingfishers rely on steep, actively eroding banks for nesting and burrowing habitat, while other breeding and migratory bird species use banks to feed on emerging insects (Graf et al. 2002). Bank erosion and channel migration produce point bars and floodplains of varying ages and elevations. These physical processes produce a riverscape mosaic with areas inundated by different flows, which creates important habitat heterogeneity used by a multitude of species (Power 1992; Richards et al. 2002).

Rivers flowing through federal lands, such as national parks and those designated as part of the National Wild and Scenic River System, are given special recognition and protections to preserve their free-flowing condition, water quality, and outstandingly remarkable values for the enjoyment of present and future generations (National Park Service 2006, 2021). The National Park Service (NPS) manages over 220,000 miles of rivers, approximately 3,750 of which are part of the National Wild and Scenic River System (Figure 1). Both NPS-managed rivers and designated Wild and Scenic Rivers (WSR) encompass various climatic, geological, and watershed settings with different histories of land use and watershed disturbance. This complexity necessitates that NPS and WSR managers evaluate bank erosion on a case-by-case basis, which requires a basic understanding of why riverbanks erode and the mechanisms by which banks fail in order to determine suitable management actions and ensure their consistency with the WSR Act (WSRA) and NPS policy. Best practices along these rivers involve preserving natural geomorphic processes, such as bank erosion, whenever possible. Alternatives to bank stabilization that allow bank erosion to continue, such as land protection measures like conservation areas and easements, should be considered before implementing bank stabilization. In certain circumstances, however, bank stabilization may be

necessary, such as when critical facilities or infrastructure are threatened and cannot be relocated. In these cases, nature-based treatments, such as those using live or dead plant material, are preferred over more traditional engineering solutions that use hard elements like rock and concrete. In some instances, such as protecting critical transportation infrastructure, more traditional engineering approaches may be needed to ensure public safety.

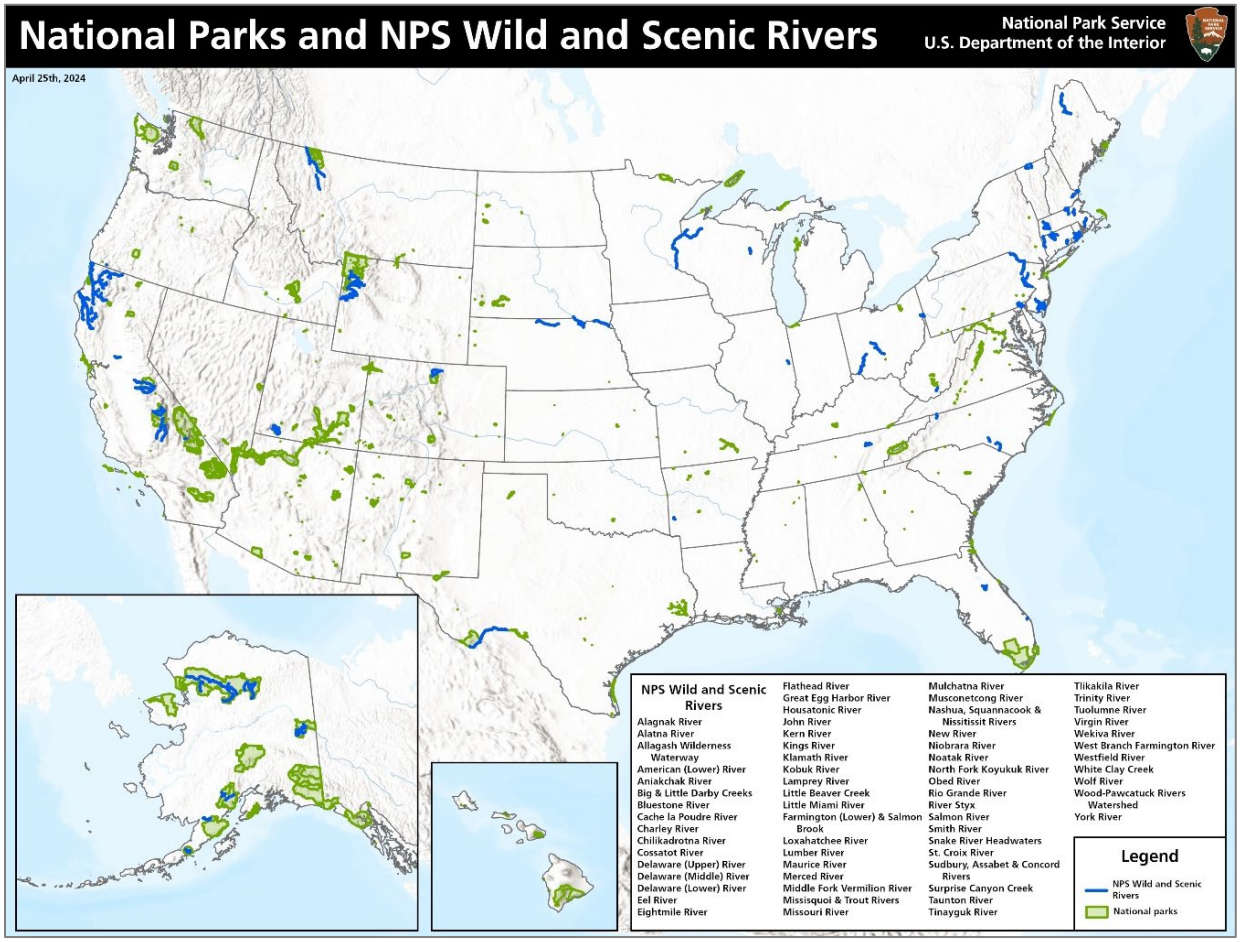


Figure 1. Wild and Scenic Rivers (blue lines) and national park boundaries (green) across the United States. NPS

The purpose of this document is to (1) provide an overview of river and geomorphic processes related to bank erosion, (2) present bank erosion management techniques, highlighting those that promote natural conditions and are most appropriate for WSR and NPS-managed rivers, and (3) present a decision tree that can be used to determine bank erosion management strategies that are most aligned with NPS and WSR values at a particular site. To accomplish this, we first provide an overview of river processes as they relate to bank erosion, including important factors that influence the rate of bank erosion and the mechanisms by which banks erode, in *River Processes Related to Natural Bank Erosion*. Next, we describe several techniques to address bank erosion and summarize each technique in an important quick-reference figure in *Approaches to Managing Bank Erosion*. Finally, we present a decision tree to select the best approach to managing a specific bank erosion

problem in *Selecting an Appropriate Approach to Managing Bank Erosion*, which is this document's most important product. We close by suggesting alternative strategies to broaden your perspective on bank erosion in *Additional Ways to Approach Management of Eroding Banks* and identify helpful resources to visit when making WSRA Section 7 determinations in *Resources for Preparing WSRA Section 7 Determinations*.

The main guidance document provides a conceptual overview and hits key points, but readers are strongly encouraged to consult the accompanying appendices to find more actionable information. It is important to recognize that this document is *not* an engineering design manual. Instead, the document should be used when evaluating streambank erosion to steer management actions toward practices that maintain the ecological and geomorphic functions of the river.

River Processes Related to Natural Bank Erosion

Factors influencing bank erosion rates

Lateral stability

The tendency of a river to adjust its position from side to side is referred to as lateral stability (Fryirs and Brierley 2012). Different rivers, or reaches within the same river, can have different degrees of lateral stability and, therefore, different rates of naturally occurring bank erosion. A river with low lateral stability may migrate quickly across the floodplain and have widespread bank erosion but be considered geomorphically stable if the channel planform, cross-sectional area, and rate of bank erosion are relatively consistent over multidecadal periods. In these laterally *un*stable systems, extensive bank stabilization projects covering long distances of the riverbank often cause undesirable secondary impacts, such as bed lowering (i.e., incision), loss of habitat, and changes in the geomorphic character of the river. Similarly, a river experiencing elevated rates of bank erosion may be adjusting to an external disturbance, and bank stabilization may also lead to secondary effects. Sometimes a rapid increase in bank retreat is temporary and not reflective of a long-term shift in lateral movement, such as after large floods or when a buffer of riparian vegetation has been removed. In these instances, emergency bank repairs can disrupt important geomorphic processes that maintain healthy terrestrial and aquatic ecosystems. All bank stabilization projects should evaluate the potential unintended impacts of bank stabilization in the planning process.

Valley setting

The ability of a river to laterally move and the composition of the riverbanks is partly dependent on the valley setting, which refers to the shape of the valley and how the river interacts with the valley walls (Fryirs and Brierley 2012). The valley setting influences whether the riverbanks are composed of alluvial sediment previously transported and deposited by the river or non-alluvial sediment, such as hillslope colluvium, terraces, or bedrock. Alluvial bank retreat is often slow and steady because the sediment is mobile and easily reworked through erosion and deposition during each flood event. Conversely, non-alluvial bank erosion is caused by hillslope failures that are abrupt, potentially problematic, and hard to predict. The focus of this guidance document is alluvial bank erosion, although many of the same bank-stabilization techniques can be applied to non-alluvial banks. When facing non-alluvial bank erosion, special care should be taken by river managers and additional input solicited from professionals with experience working in complex riverine environments and expertise in geotechnical engineering and geosciences. The success of any bank stabilization project will depend on the professional experience and expertise of the design team.

In a confined valley setting, the river touches bedrock valley walls, hillslopes, or terraces that are highly resistant to erosion for most of its reach length (Figure 2). The rate of lateral erosion in confined valleys is very slow, occurring over timescales of many thousands of years. Hillslopes and terraces touching the channel margin can be prone to landslides if river migration oversteepens the slope. Flood flows are often concentrated in narrow valleys, resulting in strong erosive forces and rapid increases in flood stage.

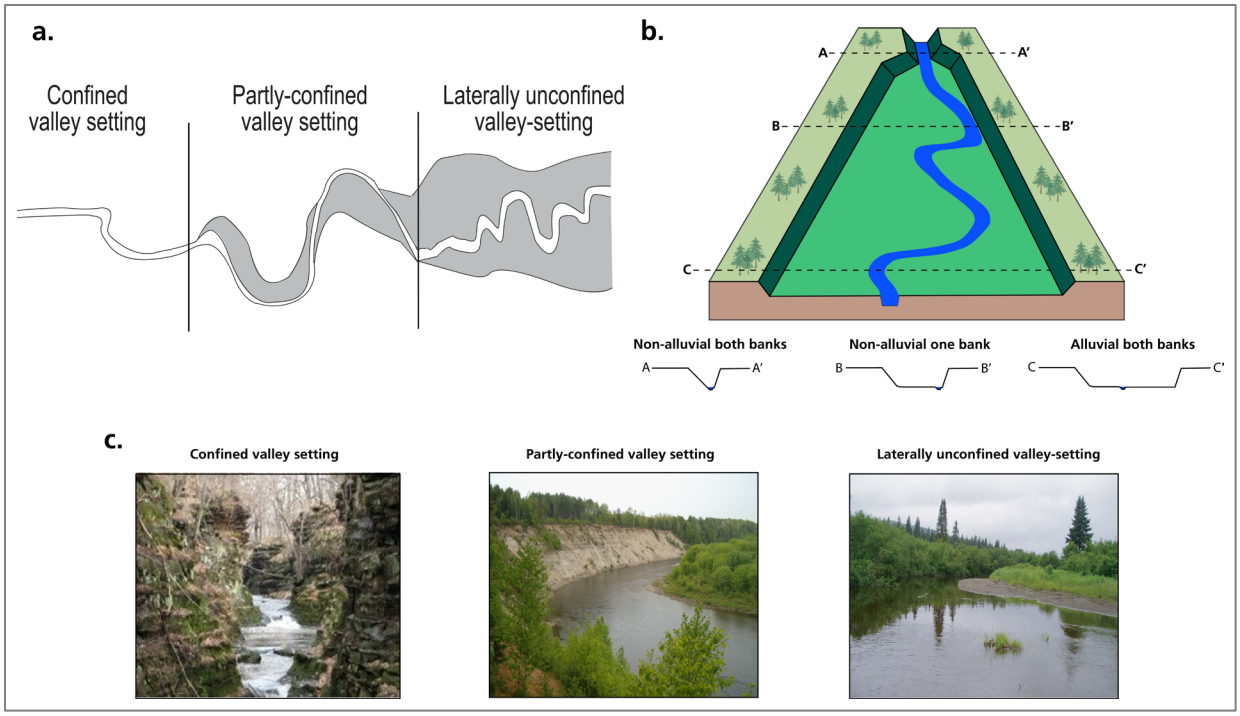


Figure 2. Depiction of the three types of valley settings. (a) Planform view of valley setting with floodplains shown in gray. The banks are alluvial where the channel touches the floodplain and non-alluvial everywhere else. (b) Schematic showing how the valley bottom and channel cross-section change in confined (A–A′), partly confined (B–B′), and laterally unconfined (C–C′) valley settings. (c) Example field photo for each valley setting. CREDITS: (a) REPRINTED WITH PERMISSION FROM FRYIRS AND BRIERLEY 2012, (b) NPS, (c) NPS

In partly confined valley settings, the river flows through a valley with discontinuous pockets of floodplain between the channel and valley walls (Figure 2). Floodplains give water space to spread laterally during floods, which dissipates erosive forces compared to the confined valley setting. The riverbanks in a partly confined valley are composed of alluvial floodplain sediment on one side of the channel and non-alluvial valley margin material (e.g., hillslope, bedrock) on the other side of the channel. Higher rates of bank erosion typically occur along the alluvial floodplain bank than on the non-alluvial valley margin, although large landslides are possible on the valley margin.

In an unconfined valley setting, the river is laterally unconstrained, and the channel is less likely to naturally touch the valley margin (Figure 2). The riverbanks on both sides of the channel are typically alluvial with a wide adjacent floodplain that provides ample space for flood flows to spread laterally. The erosive force against the banks rapidly dissipates across the wide floodplain once flood flows overtop the channel banks, as compared to the confined and partly-confined valley setting.

When evaluating a site-specific bank erosion problem, it is important to consider the character of the river to understand whether a high rate of bank retreat is expected and natural given the river type and valley setting. Although rivers in partly-confined and unconfined valleys retain their ability to migrate laterally, the degree of lateral stability and rate of bank erosion can vary. Some rivers

naturally have little lateral movement even when unconstrained by a highly-resistant valley margin, while others have high natural rates of lateral movement and bank retreat. The degree of lateral movement, and therefore bank erosion, is primarily determined by the channel slope and the volume and size of sediment the river transports with the available streamflow (Figure 3; Schumm 1985; Church 1992). Low-gradient rivers carrying fine-grained sediment (i.e., fine sand, silt, and clay) mostly in suspension, tend to form broad, sweeping meanders that have slower rates of lateral movement. As the channel slope and the amount and grain size of sediment increase, the rates of lateral movement and bank retreat also increase. For example, rivers with multiple braided gravel-bed channels tend to have faster rates of lateral movement than sand-bed meandering channels, but both conditions can be healthy and geomorphically stable.

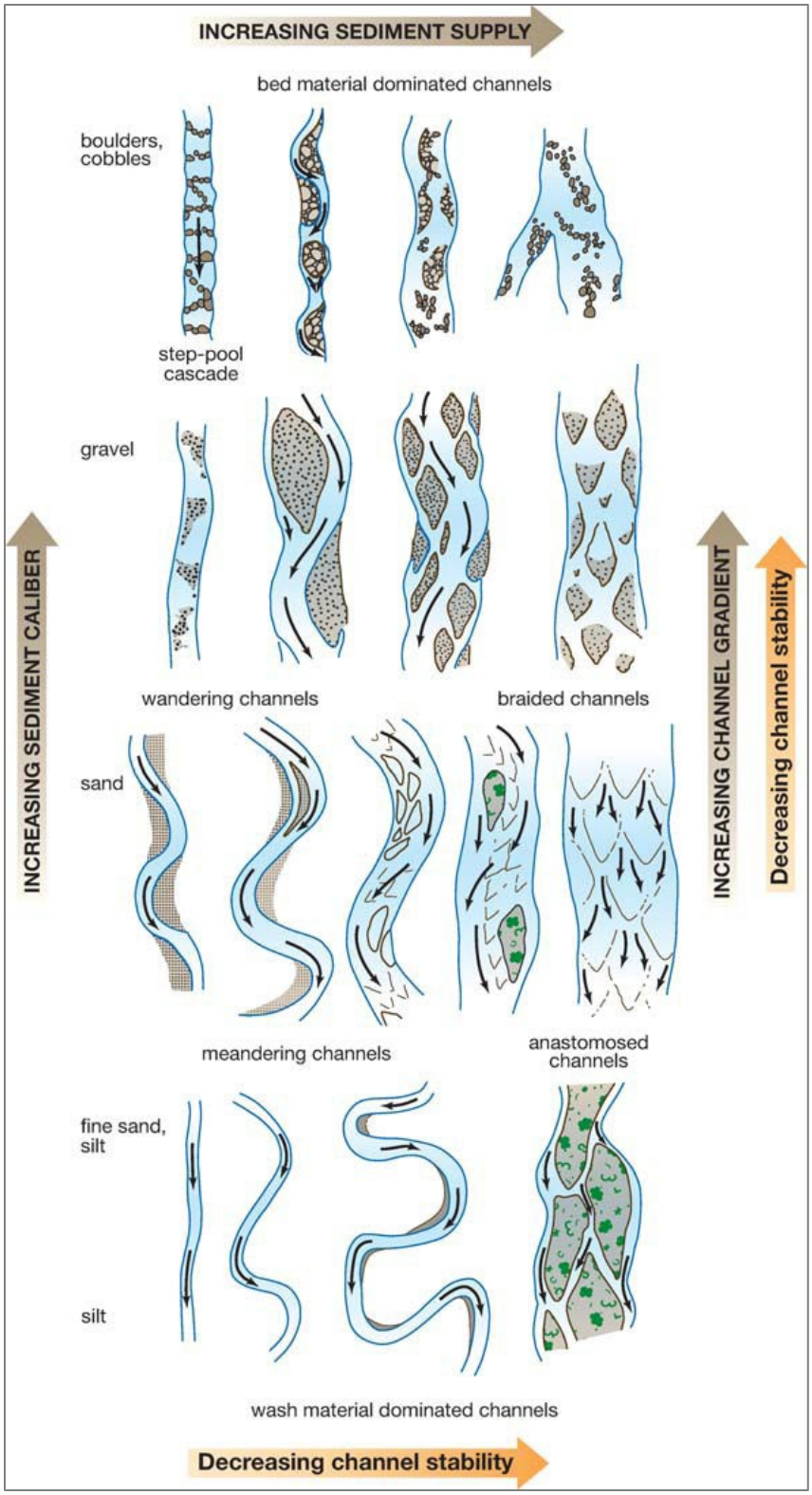


Figure 3. Alluvial river channel form as a function of sediment supply, sediment caliber (grain size), and channel gradient (slope). Channel stability (orange arrows) decreases with increasing sediment supply, sediment supply grain size, and channel slope, leading to a higher rate of bank retreat. REPRINTED WITH PERMISSION FROM CHURCH 2006

Channel pattern

Channel pattern (i.e., channel form) partly controls the style, rate, and predictability of bank erosion. Two types of river channel patterns predominate in partly-confined and unconfined valleys where lateral channel migration is possible—braided and meandering (Figure 3). Although the characteristics of bank erosion differ among braided and meandering channel forms, both conditions are geomorphically stable for that particular setting, and mitigation strategies should conform to the style of bank erosion that naturally occurs. Braided rivers have high bank erosion rates, and the location of bank erosion varies from year to year, which makes bank stabilization projects challenging. Bank erosion is an important process in braided rivers that helps maintain the braided channel pattern by providing sediment to form in-channel bars and vegetated islands (Wheaton et al. 2013). Widespread bank stabilization in these settings can have a substantial impact on the river form and character. Conversely, the location of bank erosion in meandering rivers is more predictable and generally focused on the outside of meandering bends. The highest rates of bank erosion typically occur just downstream from the bend apex (Dietrich and Smith 1984). Meander bend geometry also influences the outside bend bank erosion rate, with tighter bends migrating faster than more gradual bends (Hickin 1974; Hickin and Nanson 1984).

Natural and human-caused disturbances can change the characteristics of bank erosion as the river adjusts. When the amount of water, sediment, or the combination of the two delivered to a river changes, the river adjusts its dimensions as a result. Climate-induced changes in streamflow and sediment delivery will affect most rivers in the coming decades (East and Sankey 2020), and there might be temporary or long-term changes in lateral stability and bank retreat as rivers adjust. Bank stabilization projects intended to mitigate climate-induced changes in streamflow are likely to have unintended secondary effects, and the channel should be allowed to adjust to conditions of a changing climate whenever possible. Bed incision (i.e., lowering of the channel bed elevation) caused by human-induced changes in streamflow or sediment delivery is often associated with system-wide increase in bank erosion. Bed incision creates an entrenched channel disconnected from the floodplain, leading to increasingly higher banks that become oversteepened and unstable, causing the channel to widen through bank erosion (Figure 4). Upstream dam construction (Schmidt and Wilcock 2008; Williams and Wolman 1984), land-use change (Trimble 1981), river channelization (Galay 1983; Bledsoe et al. 2002), and near-channel grazing (Quinn et al. 1992; Wasson et al. 1998) change the amount of water and/or sediment delivered to a river, which may lead to bed incision and a subsequent increase in the bank erosion rate. Additionally, rapid changes in the channel slope caused by the removal of weirs, dams (beaver or manmade), and logjams can lead to head cutting that propagates upstream, causing localized bed incision and rapid bank retreat. Vegetation clearing from the channel banks and floodplains also dramatically affects the rate of bank retreat. For example, non-vegetated banks can erode up to five times faster than vegetated banks (Beeson and Doyle 1995), and a river can migrate through a clearcut floodplain twice as fast as a forested floodplain (Hickin 1984).

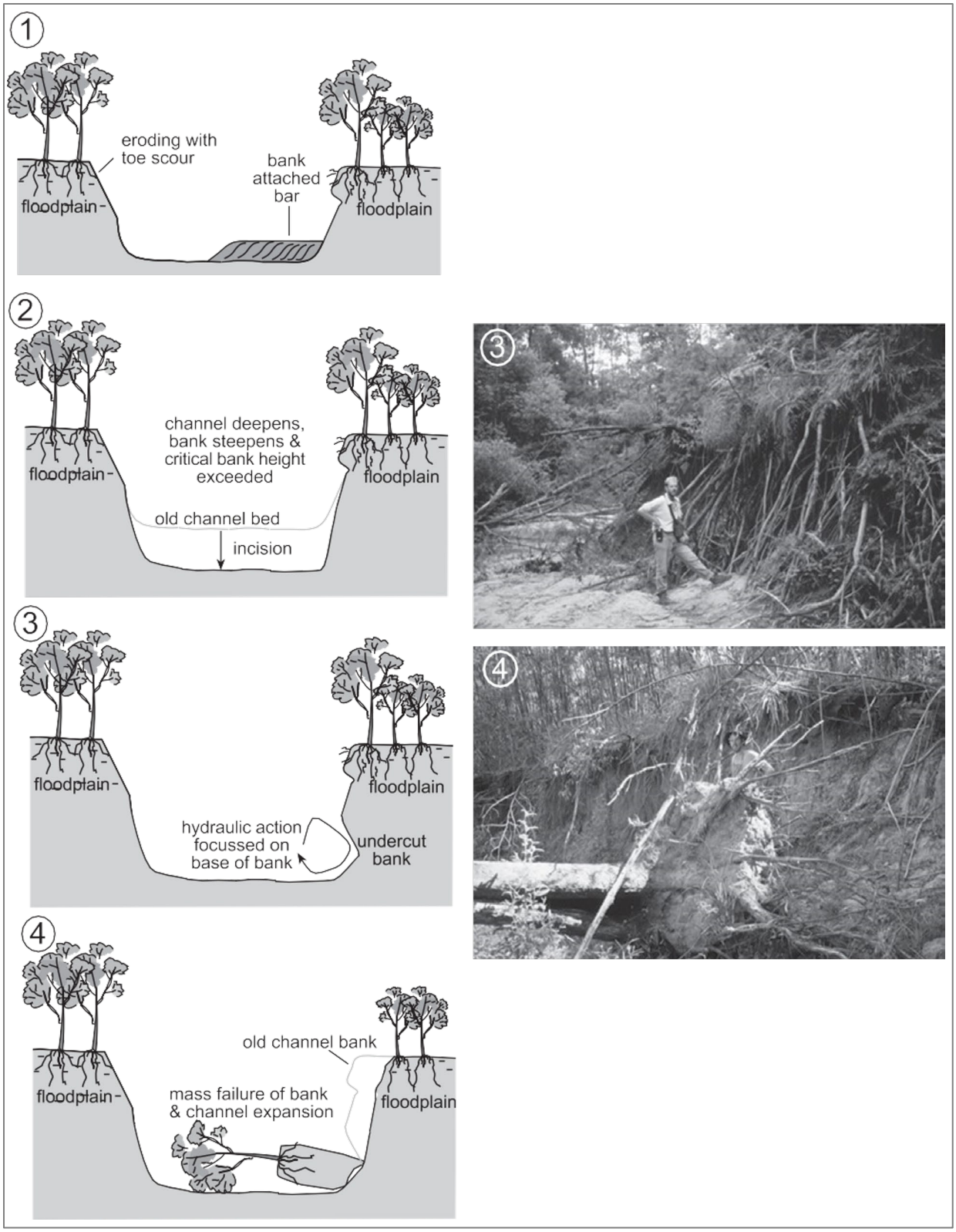


Figure 4. Cycle of bed incision leading to channel widening. When bed incision exceeds critical bank height, mass failures occur, and the channel widens. REPRINTED WITH PERMISSION FROM FRYIRS AND BRIERLEY 2012

Mechanics of bank erosion

Understanding how a bank erodes at a particular site is critical to selecting the appropriate bank stabilization technique. Bank erosion is highly variable along alluvial rivers and dependent on many factors, including channel pattern, properties of the flow, bank composition, climate, subsurface conditions, and vegetation (Knighton 1998). To summarize the key concepts, bank erosion at a particular site is strongly influenced by the properties of the bank itself, such as bank slope, sediment composition, and vegetation, along with properties of the river flow, such as how quickly water levels change, how the flow changes seasonally, how much sediment is transported by the flow, and the magnitude of floods. A more detailed and technical explanation of the mechanisms of bank erosion is provided in this section.

While intuition might suggest the flood magnitude is directly related to the bank erosion rate, the correlation is relatively weak because the bank conditions before the flood event have a large influence on the bank's erodibility. For example, large summer floods often produce considerably less erosion than smaller winter floods in warmer climates because drier banks during the summer months are stronger than saturated banks during the winter months (Wolman 1959). Conversely, banks are often frozen during the winter months in cooler climates and are thus less susceptible to erosion during winter floods. Multi-peak floods may cause more bank erosion than single-peak floods because the banks become saturated and weakened during the first flood peak and are more susceptible to erosion during subsequent peaks. These examples highlight the importance of considering the bank's material strength prior to failure in addition to the flow strength when developing a stabilization design.

Banks are composed of cohesive and non-cohesive sediment. Non-cohesive sediment consists of loose sand, gravel, cobble, and boulders, whereas cohesive sediment consists of silt, clay, and fine sand bonded by electrostatic forces between the particles. Most alluvial banks are *composite banks* characterized by coarser-grain non-cohesive sediment at the bank bottom overlain by cohesive silt, clay, sand, and organics deposited by overbank flow on a floodplain.

Bank retreat happens in two phases. First, sediment must detach from the bank, and the detached sediment generally accumulates at the bank base. Sediment can detach from the bank by fluvial entrainment (i.e., the transport of sediment by the river's flow), but it typically falls to the base of the bank first due to mass failures, which are the movement of rock or soil downslope by gravity (Figure 5). Second, the accumulated sediment must be transported downstream away from the bank base by fluvial entrainment. Bank stabilization projects often need to address both phases of bank retreat, with specific treatments intended to prevent sediment from detaching from the bank and other treatments designed to prevent erosion at the bank base.

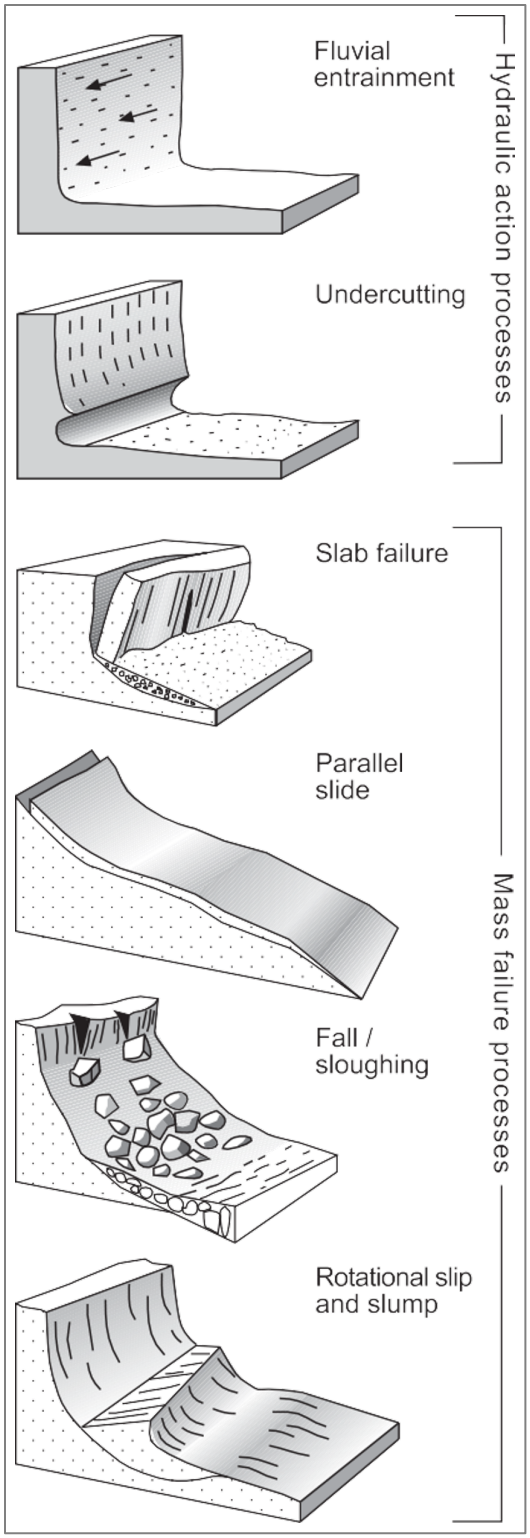


Figure 5. Sediment detaches from the bank by fluvial entrainment (hydraulic action) and mass failure. Fluvial entrainment involves the shearing of sediment from the bank by flowing water. Mass failures involve sediment moving downslope by gravity. REPRINTED WITH PERMISSION FROM FRYIRS AND BRIERLEY 2012

Bank erodibility partly depends on the bank material type and the amount of vegetation on the bank. The susceptibility of a non-cohesive bank to fluvial entrainment is directly related to the near-bank flow velocity, flow depth, and the grain size of the bank material. Coarser bank sediment, like gravel, is harder to move than finer sediment, like sand, and a higher flow velocity is needed to detach gravel from the bank compared to sand. The susceptibility of a cohesive bank to fluvial entrainment is directly related to the material cohesion, and cohesive sediment is often more resistant to fluvial entrainment than non-cohesive sediment despite having a finer grain size. For example, hard, dry banks are more resistant to fluvial entrainment than wet, saturated banks when sediments are less cohesive. Vegetation also has a strong effect on the susceptibility to fluvial entrainment, as bank vegetation dissipates near-bank velocity while the root system increases soil cohesion (Wu et al. 1999; Manners et al. 2015). Additionally, vegetation with flexible stems, such as willows and grasses, can fold during floods, acting as a blanket that protects the underlying bank sediment from fluvial entrainment (Hopkinson and Wynn 2009).

Several preparatory processes weaken (or strengthen) the bank material and strongly affect the bank's susceptibility to erode. The bank moisture content has a significant influence on bank stability. During long-duration floods or rainfall events, saturated banks may be stable during the flood peak but quickly fail as the flood recedes and the flow no longer provides support against the bank. Wetting and drying cycles also affect bank stability by creating tension cracks that promote mass failure. Freeze and thaw cycles can disaggregate banks through frost action that widens pre-existing cracks, making banks more susceptible to mass failures and fluvial entrainment.

Mass failure is the collapse of portions of the bank when gravity overcomes the resisting force of the bank material (Figure 5). The resisting force of the bank depends on the bank slope, material, and structure. For cohesive sediment, the bank's resisting force increases as the bank material becomes more cohesive and less saturated. For non-cohesive sediment, the bank's resisting force is primarily a function of the bank slope and moisture content, and drier banks with a gentler slope tend to be more stable. Plant roots can increase bank strength in non-cohesive and cohesive sediment, increasing the resisting force and reducing the bank's susceptibility to mass failure (Micheli and Kirchner 2002; Polvi et al. 2014). Large, deep-seated mass failures, such as rotational slumps (Figure 5), are rare in non-cohesive banks, where banks typically erode by fluvial entrainment, undercutting, and subsequent bank collapse. Although vertical banks are generally more prone to mass failure, stable banks can form at steep angles in cohesive sediment, and many rivers with a high suspended load have near-vertical banks that are relatively stable.

Fluvial entrainment and mass failure often work in tandem on *composite banks* (Figure 6; Parker et al. 2011). Non-cohesive sediment at the base of the bank is more erodible and preferentially scours, creating an overhanging, highly-unstable cohesive layer in the upper bank which eventually detaches and accumulates at the base, temporarily protecting the base from additional scour and retreat. However, once the river transports the failed upper bank sediment downstream, preferential scouring at the base continues, and the cycle restarts.

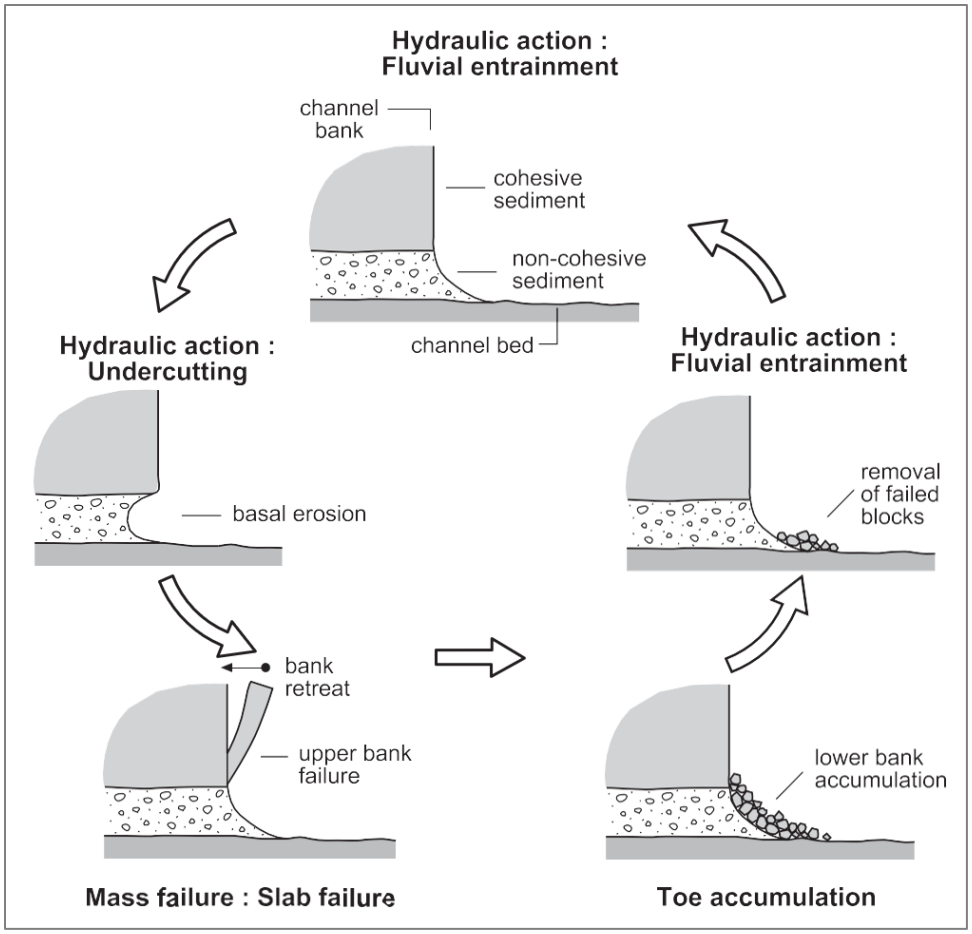


Figure 6. Cycle of bank retreat in composite banks. Fluvial entrainment preferentially scours the bank base, creating an overhanging upper bank that detaches by mass failure and accumulates that the base. The bank retreat cycle restarts once the accumulated material at the base is removed by fluvial entrainment. REPRINTED WITH PERMISSION FROM FRYIRS AND BRIERLEY 2012

Approaches to Managing Bank Erosion

This section outlines approaches to managing bank erosion and the suitability of each approach in different river settings. Before stabilizing an eroding bank, managers should first consider the importance of lateral movement to building complex, dynamic, and resilient landscapes and ask whether bank erosion can be managed by strategies other than stabilization. Measures that facilitate continued erosion within the river corridor by giving rivers the freedom and space to move are generally favored approaches on WSR and NPS-managed rivers. Example measures that allow bank erosion to continue and prioritize natural fluvial processes within river corridors include conservation easements, purchasing land along the river, and relocating infrastructure threatened by bank erosion.

Bank stabilization may be warranted in situations where erosion threatens infrastructure or facilities, developed land, or other valuable natural and cultural resources. Stabilization projects should focus on slowing the rate of bank erosion and, whenever possible, allowing for some dynamic channel behaviors that preserve the ecological functions of bank retreat. However, in certain circumstances, fully arresting bank erosion may be necessary to protect infrastructure or natural and cultural resources. Stabilization techniques that significantly incorporate vegetation or wood in the design, commonly referred to as bioengineering or biostabilization, are preferred over inert materials, such as riprap and concrete on WSR and rivers managed by NPS.

There is a range of approaches used to manage bank erosion, with each approach having its pros and cons, making it more or less suitable for WSR and NPS-managed rivers. Figure 7 summarizes these approaches and evaluates their applicability to WSR and NPS rivers. Each approach in Figure 7 has an associated factsheet in Appendix 1 that provides additional information on the technique, including important considerations when evaluating its suitability for use on WSR and NPS-managed rivers, and a checklist for reviewing bank stabilization plans. Managers are encouraged to use these factsheets when evaluating approaches to managing bank erosion and reviewing bank stabilization plans.

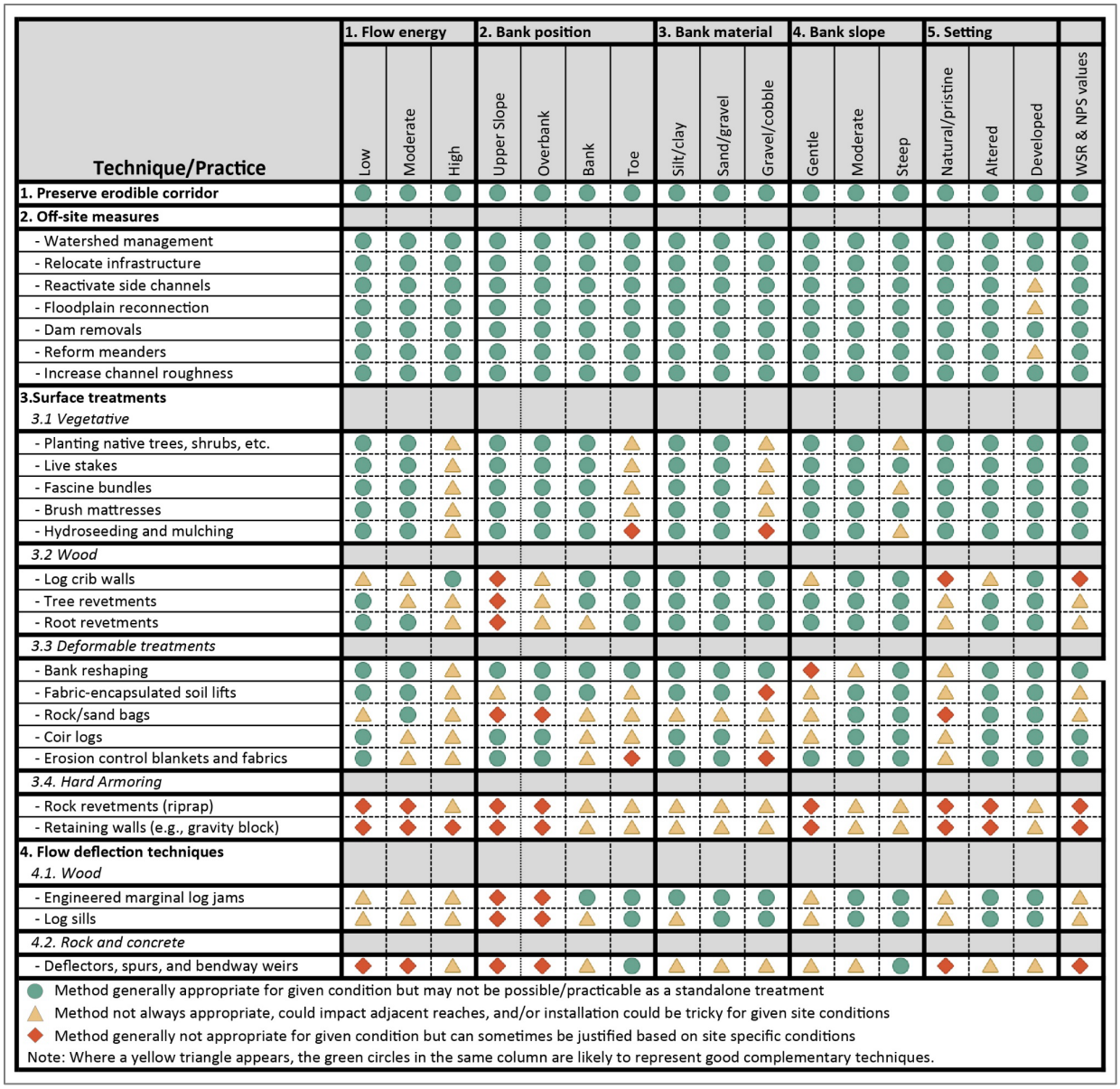


Figure 7. Approaches used to manage bank erosion and their appropriateness for use on WSR and NPS-managed rivers. Green circles indicate the approach is generally appropriate. Yellow triangles indicate the approach is not always appropriate. Red diamonds indicate the approach is generally not appropriate. Refer to the text for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 2. NPS

Each technique for managing bank erosion should be evaluated in the context of the specific river reach in which it is being considered. Figure 7 can be used to evaluate the suitability of an approach based on site-specific conditions and the general characteristics of the river reach. Rows in Figure 7 list different approaches, which fall into five categories: (1) preserve the erodible corridor and allow bank erosion to continue unimpaired, (2) off-site measures that reduce erosive energy approaching the bank or move a conflict away from the river, (3) vegetative surface stabilization treatments that increase the bank strength, (4) wood or rock surface treatments that protect the bank from the flow,

(5) deformable surface treatments that aim to slow the rate of bank retreat while preserving natural channel processes, and (6) flow deflection techniques that redirect erosive energy away from the bank. Bank stabilization projects often use multiple techniques, such as log jams deflecting flow away from the toe of the bank with vegetative approaches stabilizing the upper bank. The columns in Figure 7 are variables to consider when evaluating the suitability of the various bank erosion management approaches at a given site. These variables, as well as the treatment types, are described below to provide a fuller context for using Figure 7.

Techniques to address bank erosion

This section describes the various techniques that can be used to address bank erosion. These techniques are the rows in Figure 7. Refer to the factsheets in Appendix 1 for more information.

1. Preserve the erodible corridor

Preserve the erodible corridor where riverbank erosion can occur unimpeded. An erodible corridor is a defined area where the river has the space to freely migrate and laterally erode (Piégay et al. 2005; Figure 8). The erodible corridor is also known as the channel migration zone, fluvial territory, freedom space, fluvial corridor, and fluvial hazard corridor. Regardless of the name used, allowing space for bank erosion to proceed is the preferred option for managing bank erosion on WSR and NPS-managed rivers. The width of the erodible corridor can vary along the river length depending on factors such as geologic controls, soil characteristics, and valley confinement. This approach preserves the geomorphic processes and the ecological benefits of bank erosion while also protecting wetlands and riparian zones. Corridor preservation can be facilitated by diverse and creative methods such as land acquisition, conservation easements, public outreach, landowner education and stewardship, moving infrastructure outside the corridor, or simply monitoring bank erosion to determine the severity of bank retreat and whether there is an immediate threat.

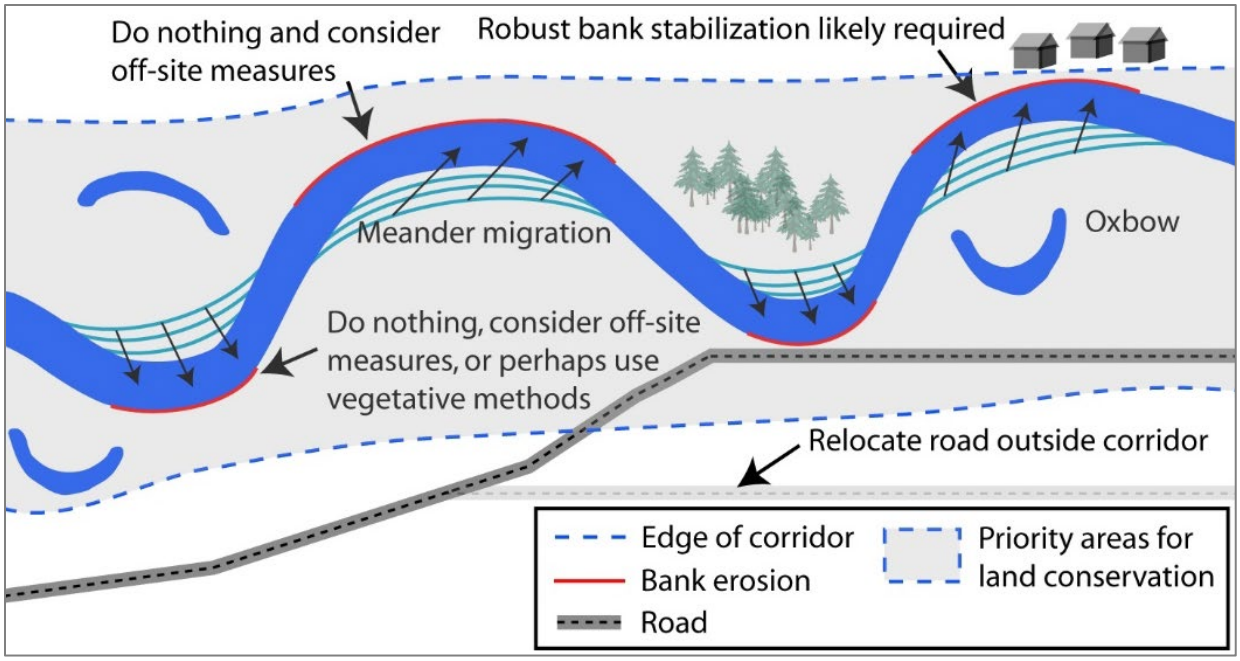


Figure 8. Schematic depicting the erodible corridor (gray area within dashed blue lines) and management measures that can be implemented to preserve the erodible corridor, allowing bank erosion to proceed unimpeded. NPS / FIELD GEOLOGY SERVICES, LLC

2. Off-site measures are activities

Off-site measures are activities that slow bank erosion without using site-specific stabilization techniques. Several stream restoration and watershed management actions qualify as off-site measures, including those that occur in the channel upstream and those that occur within the surrounding landscape. Instream practices include dam removal; reactivation of side channels closed by human activities; removal (or setback) of structures that separate the channel from its floodplain, such as berms and levees; livestock fencing; and encouraging meander formation on straightened reaches. Upland or watershed management practices include redirecting surface runoff to prevent gullying or subsurface piping; revegetating landscapes; stormwater runoff control; and removing conflicts from the near-bank environment, such as relocating a susceptible road, boat ramp, campground, water supply intake, diversions, etc. Off-site measures often include collaboration with other landowners and stakeholders. Undertaking off-site measures may result in longer-term bank stability with benefits that extend beyond stabilizing the specific eroding bank of interest. Opportunities for off-site measures should always be sought as part of bank stabilization efforts. Even if no action is ultimately undertaken off-site, exploring potential options helps stakeholders identify the underlying causes of bank erosion, anticipate the potential for continued bank erosion, and design more effective bank stabilization projects.

3. Surface treatments

Surface treatments are bank stabilization techniques that protect the bank sediments from fluvial entrainment by covering the bank with different types of erosion-resistant material.

3.1 Vegetative surface treatments

Vegetative surface treatments are bank stabilization techniques that rely on vegetation to increase the resisting forces of the bank and decrease the bank's susceptibility to fluvial entrainment by increasing roughness and slowing near-bank flow velocity. In addition to simply planting trees or spreading grass seed, vegetative treatments include techniques that grow vegetation from live stakes, fascine bundles, brush mattresses, and hydroseeding. Fascine bundles and brush mattresses generally include dormant branches that will root once staked down on the bank and partly covered with soil. While these techniques provide some initial protection, they are particularly vulnerable immediately after planting; however, they do strengthen as vegetation matures. These treatments generally perform best in low-energy environments or in conjunction with other techniques that provide stabilization until the vegetation matures. Vegetative surface treatments are often combined with bank reshaping to lay back steep, unstable slopes. Projects using vegetative treatments should select appropriate native plant species based on local climate, soils, shade tolerance, and rooting character (see *Native Vegetation Planting Fact Sheet* in Appendix 1). While typically combined with other approaches, vegetative surface treatments are consistent with WSR values and NPS management policies, and they should be integrated into WSR and NPS-managed river projects whenever possible.

3.2 Wood surface treatments

Wood surface treatments are traditional techniques for bank protection that cover the bank surface with wood to armor the bank and prevent fluvial erosion of underlying material. Wood treatments provide further protection against fluvial entrainment by increasing the bank roughness and slowing the near bank flow. Common treatments include log crib walls, tree revetments, and root revetments. Wood-based treatments are more consistent with WSR and NPS values and should be chosen over rock-based treatments whenever possible. Wood-based projects can outlast rock-based projects because complexes of well-anchored logs act as a single unit that is less likely to be displaced than individual rocks. Wood-based projects also provide more complex habitats and are less likely to transfer erosive forces downstream because their surface roughness dissipates energy, especially when roots are included. Because wood is buoyant and subject to decay, wood treatments must be carefully anchored or ballasted and should be constructed with rot-resistant species (see Appendix 1, Table 1). Several anchoring methods are available, including driving "key logs" into the bed and banks (*preferred approach for wood treatments on WSR and NPS-managed rivers*), using rock as ballast, wedging logs between standing trees, fastening logs with threaded rods, bolts, or rebar, and lashing with rope, steel cable, or chain. Where it is necessary to fasten logs, using heavy biodegradable cordage rather than steel cable, chain, or rods can minimize hazards to recreational use. Wood and rock surface treatments can be combined with vegetative treatments located higher on the bank or interplanted within the structure.

3.3 Deformable surface treatments

Deformable surface treatments are often intended to provide temporary stability before complementary techniques, like vegetative surface treatments, take hold. For example, erosion control blankets are typically laid over an existing or regraded bank, while soil lifts are used to create and/or maintain a steeper slope. In either case, complementary vegetation is typically planted within

the treatment. Deformable surface treatments slow the rate of bank retreat and do not permanently alter natural river processes, consistent with WSR and NPS values. However, securing deformable treatments can be challenging in high-energy settings. We include bank reshaping as a deformable surface treatment, which is further explained in the bank reshaping factsheet in Appendix 1.

3.4 Hard Armoring

Hard Armoring is a surface treatment that uses inert materials, such as concrete or rock riprap and rock walls, to arrest bank erosion and is intended to withstand high erosive forces. Hard armoring is inconsistent with WSR and NPS values, and rock-based projects have a greater potential to translate bank erosion issues downstream. Hard armoring should only be used when no other treatment is viable and there is an immediate need to protect critical infrastructure. These treatments are typically used in high-energy settings where bank erosion threatens critical infrastructure or valuable resources.

4. Flow deflection

Flow deflection treatments reduce the erosive force acting against the bank by redirecting flow away from the bank toward the center of the channel. Deflected flow leaves an area of slack water along the bank where sediment often deposits between structures and becomes colonized by vegetation, further protecting the bank. Flow deflection structures typically use rock or wood that extends out into the channel from the bank, although they can be detached from the bank and located fully within the channel.

4.1 Wood

Wood deflectors include log sills on smaller streams and engineered marginal log jams on larger rivers. Log sills and engineered marginal log jams mimic natural features found along the banks of rivers in forested watersheds and are the preferred flow deflection treatment for WSR and NPS-managed rivers in forested ecosystems.

4.2 Rock and concrete

Rock deflectors (i.e., barbs, spurs, and groins) consist of a line of boulders angled upstream to redirect flow away from an eroding bank. Rock deflectors are built in a series along the entire length of the eroding bank. Flow deflection structures can also be built with earthen materials that are faced with large rock or concrete blocks. While flow deflector structures built with rock and other earthen materials are effective, they do not form naturally and are less well-suited for WSR and NPS-managed rivers.

Variables influencing the applicability of techniques to manage bank erosion

This section describes factors to consider when evaluating techniques to manage bank erosion at a given site (i.e., columns in Figure 7). These factors relate to properties of the bank itself and the larger landscape and watershed setting.

1. Flow energy

Flow energy is the work flowing water does to erode the channel bed and banks and transport sediment. Flow energy is related to the river's position in the watershed and degree of valley

confinement, with decreasing flow energy from mountainous to lowland plains settings. Flow energy is higher in steeper, confined valley settings and where a river has less access to a floodplain to dissipate energy. The form and characteristics of a river are related to the river's flow energy.

- Low flow energy rivers have a relatively flat channel slope with slow-moving water over a silt, clay, or sand bed. Sediment is mainly transported in suspension, and banks are typically composed of fine-grained cohesive sediment. Low-energy rivers occur in unconfined valley settings in lowland plains. Broad, continuous floodplains provide significant space for flood flows to spread laterally once water overtops the channel banks, reducing the erosive force against the banks during overbank floods. Long-duration overbank floods can saturate the banks, significantly reducing their stability as flood flows recede.
- Moderate flow energy rivers have a moderate channel gradient with somewhat faster-moving water over a bed composed of sand- and gravel-sized sediment. Sediment is transported as a combination of bedload and suspended load that forms composite banks with finer-grained sediment overlain on a coarse-grained base. Moderate flow energy rivers typically occur within partly-confined and unconfined valley settings and have a meandering or braided channel pattern. Floodplains form between the channel and valley margin, allowing floodwaters to spread laterally, reducing the erosive force of floods compared to the confined valley setting. The channel cross-section may have alluvial and non-alluvial banks.
- High flow energy rivers have a steep channel gradient with fast-moving water over a bed composed of gravel- to boulder-sized rocks. Most sediment is transported as bedload in a single, straight channel. High-energy rivers are typically found higher in the watershed in mountainous settings within confined valleys where the channel regularly touches the valley margins. Flood flows are concentrated in narrow valleys with sparse floodplains, generating high erosive forces during floods. The rate of lateral movement is slow, but hillslopes and terraces touching the channel margin can be unstable and generate large sediment inputs. Stabilization projects on hillslopes and terraces are challenging, as erosive forces remain high during flood flows, and geotechnical engineering is often required to address slope stability issues.

2. Bank position

Bank position is the relative elevation on the bank. The erosive force of flowing water changes with elevation and, therefore, bank position. The relative elevation on the bank, along with soil type, groundwater conditions, and climate, also affects the water available for vegetation.

- The *toe* is at the bottom of the streambank below the baseflow water level (Figure 9). The streambank's toe typically experiences the highest erosive forces and has the greatest fluvial entrainment. Stabilizing the toe zone is essential to the success of most bank stabilization projects.

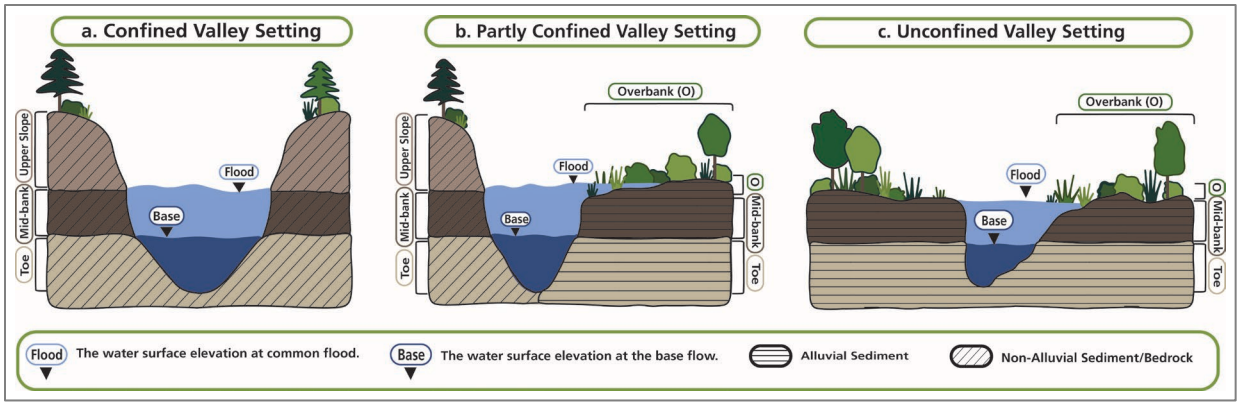


Figure 9. Schematic of bank position in (a) confined, (b) partly-confined, and (c) unconfined valley settings. Alluvial and non-alluvial banks are shown as horizontal and diagonal hatching, respectively. Transitions from toe-to-bank and from bank-to-upper slope are defined by the base flow and common flood elevations, where base flow is the sustained discharge between runoff events and the common flood is the annual high flow discharge that occurs most years. The lateral extent of the overbank position is the width of the active floodplain. NPS

- The *bank* is the main portion of the streambank and is located above the baseflow elevation and below the overbank position (Figure 9). The strength of the bank material is affected by preparatory processes, such as wet/dry and freeze/thaw cycles. The bank is often vegetated with quickly colonizing species.
- The *overbank* is above the elevation where water begins to spill onto the floodplain. The overbank is composed of alluvial sediment in the active floodplain. In an unconfined valley setting, the overbank position generally lines both sides of the channel (Figure 9c). In a partly-confined valley setting, floodplains are narrower or discontinuous and the overbank may only be present on one side of the channel while the other bank is a non-alluvial valley margin (Figure 9b). In a confined valley setting, the floodplains are absent, so the overbank does not exist (Figure 9a). The overbank can be vegetated with flood-tolerant species (e.g., willow, dogwood, alder, birch) or upland species.
- The *upper slope* is the non-alluvial valley margin above the bank position. The upper slope occurs where the channel touches the valley margin in partly-confined and confined valley settings (Figures 9a and b). Stabilizing tall, non-alluvial banks can be difficult and requires specialized professional expertise (e.g., geotechnical) because strong erosive forces can continue to act on the upper slope.

3. Bank material

Bank material is the grain size and cohesiveness of the sediment at the position where the stabilization treatment is applied. Many rivers have composite banks composed of an upper fine-grained cohesive layer over a coarser-grained, non-cohesive layer at the toe. Toe stabilization is essential, and consideration should be given to the grain size of the toe material when designing the project.

- *Silt/clay* is fine-grained cohesive sediment deposited by overbank flooding. Its structure often facilitates steeper banks, water retention for vegetation, and interactions with dynamic physical processes like shrink-swell as clay is alternately dried and rewetted.
- *Sand/gravel* is non-cohesive sediment that is small-to-medium sized. This sediment size often occurs at the bank toe but can extend through the bank in high energy, arid, and cold environments. Sand/gravel has poor water retention and internal stability.
- *Gravel/cobble* is non-cohesive sediment that is larger and typically occurs at the bank toe. Its presence suggests a high-energy setting with substantial erosive forces. Gravel/cobble has very poor water retention and internal stability.

4. Bank slope

Bank slope is the angle of the streambank. Bank reshaping can modify this attribute.

- A *gentle* bank slope gradually rises from the channel bed to the floodplain. Gentle slopes are common on the inside of meander bends and are ideal for plantings and vegetative treatments.
- A *moderate* bank slope has an intermediate bank steepness. Bank stabilization treatments could include wood surface treatments for the toe of the bank and deformable or vegetative surface treatments on the bank. Bank reshaping to lower the slope can increase the effectiveness of bank treatment.
- A *steep* bank slope has an angle that approaches vertical. Steep banks are mostly found on the outside of meander bends or along incised channels. Bank reshaping can reduce or eliminate the need for hard armoring and rock surface treatments and facilitate planting for vegetative surface treatments as long as the erosive forces at the bank toe are addressed.

5. Setting

Setting refers to the local landscape conditions in terms of the degree of human-induced modification.

- *Natural* and *pristine* settings are landscapes largely untouched by human disturbance where ecological processes continue unimpeded. Management actions that allow bank erosion to continue are strongly encouraged in these settings. Stabilization treatments that are more natural and less engineered, such as vegetation or wood surface treatments, are most appropriate in this setting.
- Partially *altered* settings are largely undeveloped landscapes with limited signs of human activity apart from forestry and agriculture. Management actions that allow bank erosion to continue are encouraged in these settings. Bank stabilization techniques that incorporate vegetation and wood treatments, including flow deflection, are more appropriate than hard armoring and rock deflection structures in this setting.
- *Developed* landscapes have human alterations and infrastructure, such as roads, bridges, buildings, or channel alterations. There is often less space for bank reshaping and vegetation

treatments in developed landscapes. Hard structural treatments, such as rock armoring and deflection, are still discouraged but may be deemed necessary in this setting.

WSR & NPS values

WSR & NPS values describe the compatibility of each technique to address bank erosion (i.e., rows in Figure 7) with WSR and NPS protections and management priorities. In general, if stabilization is required, more natural and deformable methods are favored over traditional engineering techniques that use inert material. This category's color coding deviates from the definition of color codes for the other categories in Figure 7. For this category, Green = most compatible with natural processes and WSR and NPS priorities, Yellow = intermediate, and red = least desirable and most incompatible with natural processes and WSR and NPS priorities.

Selecting an Appropriate Approach to Managing Bank Erosion

This section presents a decision tree that guides river managers through a list of sequential questions to ensure bank erosion management strategies most aligned with WSR values and NPS policies are considered first, with less desirable approaches being selected only if favored techniques are deemed unsuitable (Figure 10). The decision tree in Figure 10 is intended for general application and cannot capture all site-specific conditions, so it should be used as a starting point to brainstorm approaches for managing bank erosion. As river managers work through the decision tree, additional information related to the characteristics of bank erosion, how bank erosion rates have changed over time, and historic and ongoing watershed disturbances will be necessary. Methods to evaluate the cause of bank erosion and the history of watershed disturbance can be found in Appendix 2.

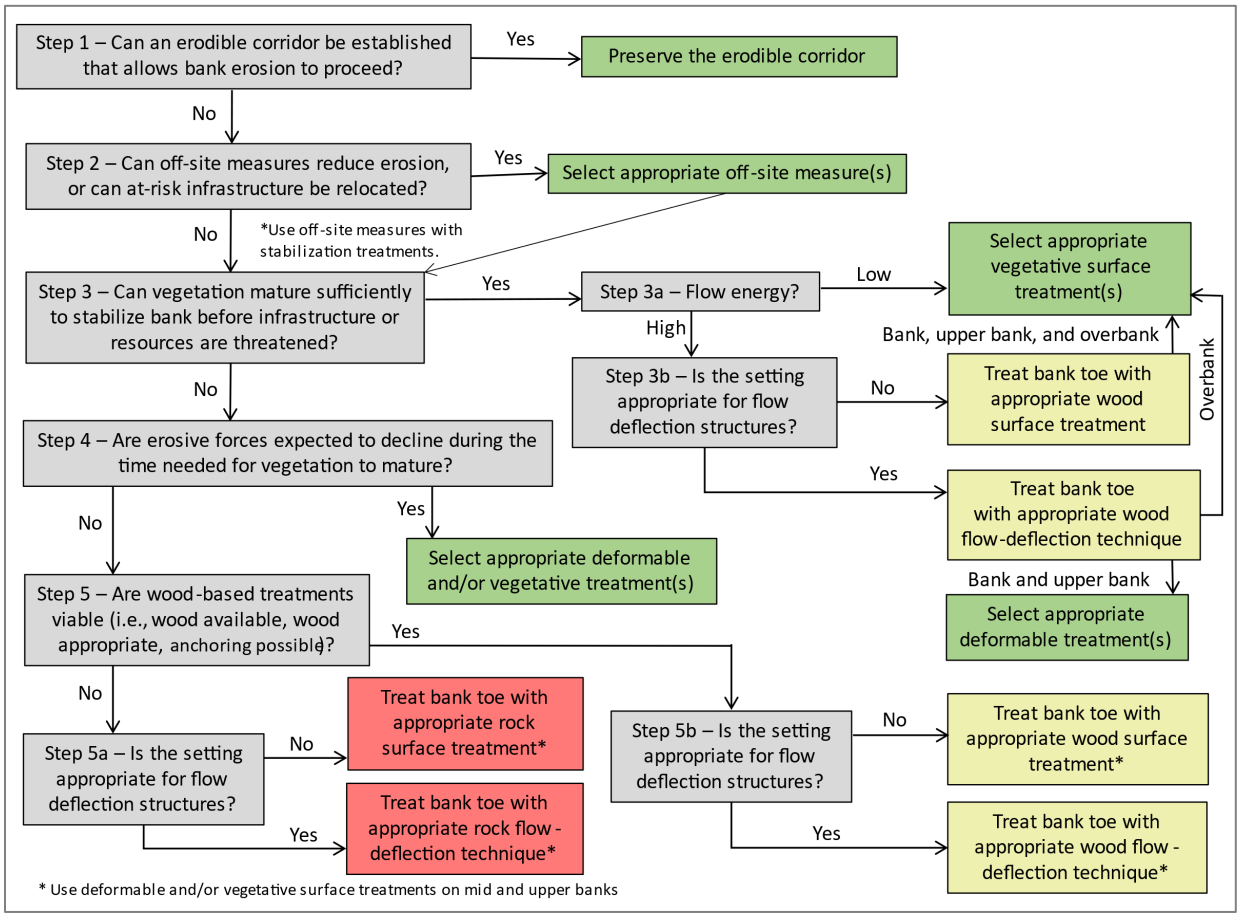


Figure 10. Decision tree to ensure bank erosion management strategies are most aligned with WSR values and NPS policies given the site constraints. The colored boxes represent a continuum of bank erosion management strategies going from more (green) to less (red) aligned with WSR values and NPS policies. NPS / FIELD GEOLOGY SERVICES, LLC

Step 1: *Can an erodible corridor be protected that allows bank erosion to proceed?* Best practice on WSR and NPS-managed rivers is to explore whether erosion can be allowed to continue before stabilization is proposed. An erodible corridor is an area where the river is allowed to freely migrate. Defining the extent of the erodible corridor will require a thorough geomorphic analysis, such as using methods described in Piegay et al. (2005). Supplementary measures may be needed to allow the river to migrate freely within the defined corridor, such as land acquisition, conservation easements, and landowner stewardship. Public outreach and education are important components of these measures. The feasibility of using an erodible corridor strategy is partly dependent on whether infrastructure, critical resources, or WSR Outstandingly Remarkable Values are at risk from bank erosion, and assessing this risk requires information on the rate and trajectory of erosion. Historical aerial photographs and topographic maps, old surveys found at historical societies, and interviews with long-time residents can help establish long-term bank erosion rates and any history of watershed disturbance. If no infrastructure or valuable resource is present, or, if they are present, but unlikely to be impacted by bank erosion within an agreed-upon timeframe, then taking no action and allowing the river to move laterally is the preferred option, and ongoing monitoring is encouraged.

Step 2: *Can offsite measures reduce erosion, or can at-risk infrastructure be relocated?* The potential for off-site measures should be considered before deciding that bank stabilization is required. One category of off-site measures is relocating valuable resources or infrastructure, such as a trail or road, away from the river. Under this scenario, bank erosion can continue because it no longer represents a threat. A second category of off-site measures is land management practices that help slow runoff, such as revegetating a denuded watershed. While off-site measures may only partially reduce the need for bank stabilization, they may be effective enough to facilitate bank stabilization treatments more aligned with WSR values and NPS management policies and should be pursued in conjunction with other bank stabilization treatments whenever possible.

Step 3: *Can vegetation mature sufficiently to stabilize the bank before infrastructure or resources are threatened?* If the distance to at-risk resources is large and/or the erosion rate slow, then there may be time for vegetation to stabilize the bank. Vegetation can require several years of root growth to provide ample stabilization. This timeframe is highly dependent on local climate, species, discharge, erosive energy, and channel morphology.

Step 3a: *Are erosive forces on the bank low or high?* Hydraulic models can calculate the erosive force exerted on the bank by flowing water, which can be compared with the maximum force that various bank stabilization materials can withstand. In the absence of a hydraulic model, the near-bank flow energy can be assessed by noting whether (1) the channel is confined or has an accessible floodplain to release flow energy, (2) the erosion occurs along a sharp bend where higher erosive forces are expected, or (3) vegetation is well-established at the base of the bank or elsewhere nearby, indicating low-energy conditions. Low-energy environments offer more favorable conditions for bank stabilization approaches that are consistent with WSR values and NPS management policies. However, even in high-energy environments, hard armoring is often not needed and should be avoided whenever possible.

Steps 3b, 5a, and 5b: *Is the setting appropriate for flow deflection?* Deflecting flow away from an eroding bank can be an effective approach in wider channels where there is room to shift the flow off the eroding bank without redirecting it to the opposite side of the channel. Where appropriate, wood flow deflection techniques are preferred over wood or rock surface treatments because they reduce near-bank erosive forces instead of simply attempting to resist them. Flow deflection using log jams mimics natural instream wood features, so their use is preferred on WSR and NPS rivers compared to rock deflectors that lack natural analogs.

Step 4: *Are erosive forces expected to decline during the time needed for vegetation to mature?* Bank erosion rates can vary as the river adjusts to short- and long-term changes in watershed conditions. For example, erosion caused by human-altered streamflow in a confined valley setting will likely persist for decades. In contrast, high bank erosion rates may occur during a single large flood, but bank erosion will slow as the channel recovers, requiring less robust bank stabilization techniques. Vegetative and deformable treatments can provide ample stability when erosive forces are expected to decline. Understanding how the rate of bank erosion might change in the future often necessitates specialized expertise in geomorphology to evaluate how the channel is recovering and understand how the channel might respond to future disturbances.

Step 5: *Are wood-based treatments viable?* Wood and wood jams naturally occur in most rivers, although this condition is often obscured by long histories of human removal of wood from channels. Wood-based bank stabilization is a viable means of bank stabilization in forested settings, especially in higher-energy settings where deformable and vegetative treatments may be inadequate. Wood-based treatments are preferred over rock-based treatments because of their more natural appearance, potentially longer functional life, lower likelihood to transfer erosive forces downstream, and habitat benefits.

Step 5a: *Hard armoring, when need is demonstrated, is the only suitable option.* Hard armoring should only be implemented when critical infrastructure or facilities are immediately threatened by bank retreat and other suitable treatment options were not identified in steps one through five. Projects should demonstrate there are no other viable alternatives to hard armoring if this treatment technique is proposed to mitigate bank erosion. Hard armoring frequently transfers erosive forces downstream and hinders riverine ecosystem functions. Hard armoring should be avoided whenever possible on WSR and rivers managed by NPS.

Additional Ways to Approach Management of Eroding Banks

Learning more about the watershed and the history of disturbance will help river managers make informed management decisions, particularly when reviewing proposed water resource projects on WSR (i.e., Section 7 determinations). Per Section 7 of the WSRA, federal-administering agencies must review any water resource projects receiving federal assistance that are proposed for a WSR. Water resource projects include bank stabilizations, revetments, and any activity within the riverbed and banks (below the ordinary highwater mark) that is intended to address bank erosion. The below list describes approaches to evaluate the history of watershed disturbances and bank stabilization projects in the river system of interest. Additional valuable information can be found in Appendix 2. The approaches outlined below apply specifically to WSR Section 7 determinations, as well as more broadly to management decisions for NPS-managed rivers.

- ***Outreach*—**An effort should be made to connect with landowners, agencies, businesses, environmental groups, land trusts, and other individuals involved in local river issues, including management of bank erosion. Learning from past successes and failures is invaluable. A highly qualified professional who is experienced in implementing bank erosion management techniques consistent with WSR values and NPS management policies is crucial to the project's success. Who has worked on bank stabilization projects in the past? Why was a project completed in a particular way? What contractors in the area have completed bioengineering projects? Where might native plants for vegetative treatments be sourced? Answering these questions long before a Section 7 determination needs to be made can steer the project toward successful bank stabilization treatments that are also consistent with the WSRA and park management policies.
- ***Further reading*—**This report's Appendix 3 contains hyperlinks to several manuals and websites focused on bioengineering techniques for bank stabilization, highlighting the best examples for WSR and NPS managers. These resources provide information on bioengineering techniques and native plants in different regions nationwide. Publications on local geology, soils, and watershed history are also helpful in contextualizing bank erosion for a given location.
- ***Investigate watershed history*—**Increased bank erosion rates are often caused by human activities, including events from hundreds of years ago. Visiting historical societies and museums and speaking with long-time residents are excellent ways to learn more about past human activities that may have impacted the river and its bank stability. The recent history of flooding is also helpful in understanding the cause of recent bank erosion. Available flow gages can be used to understand the timing of past floods.
- ***Tour the watershed*—**River managers should become familiar with the contributing watershed, including the river and tributaries upstream from a potential project and the surrounding uplands. You can tour the watershed by driving, hiking, or floating down the river and noting where bank erosion and sediment deposition occur in addition to other aspects of watershed conditions (Figure 11). How common is bank erosion? Does bank

erosion occur in consistent locations, like on the outside of meander bends? Note the frequency and type of bank stabilization and other relevant conditions, such as tributary junctions, bedrock outcrops, high riverbanks, dams, and bridges. Upland conditions, like impervious surfaces, vegetation patterns, and topography across the watershed should also be noted, as these watershed characteristics influence how water is delivered to the project reach before it meets an eroding bank.

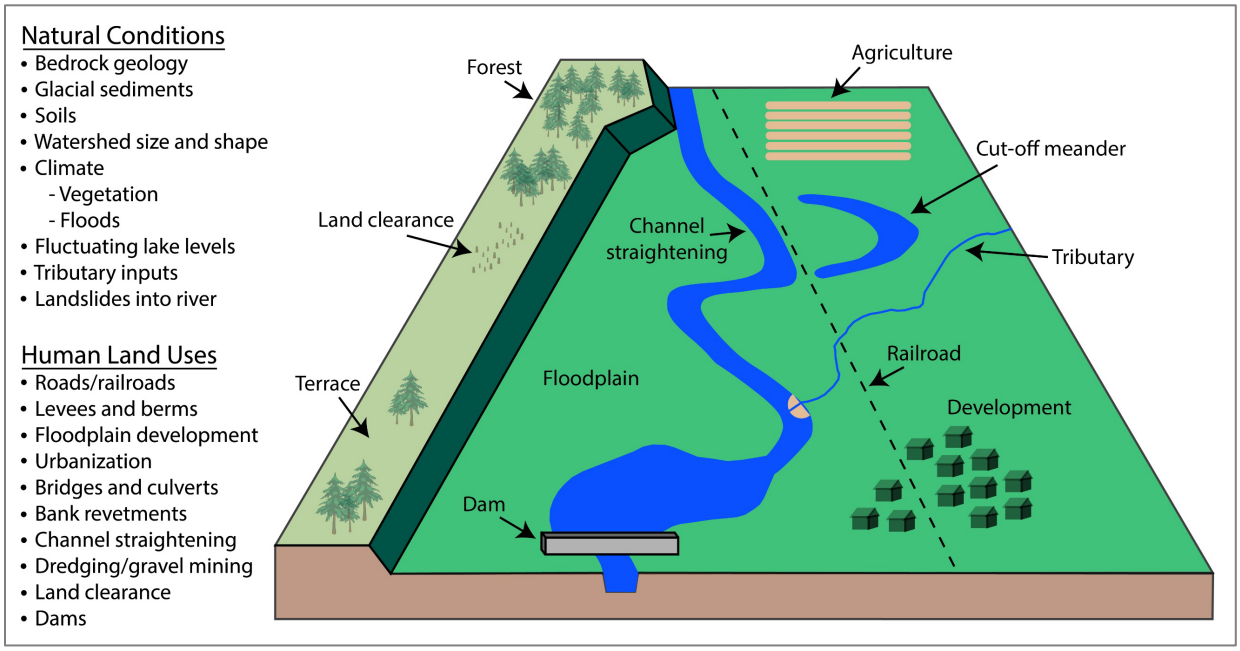


Figure 11. Overview of watershed conditions that are useful to note during a watershed tour. Take note of natural conditions, such as the location of landslides, erosion/deposition, tributary junctions, grain size of sediment on the bed and banks, and human land use and development, such as levees, bridges, bank stabilization, dams, and floodplain development. NPS / FIELD GEOLOGY SERVICES, LLC

- *Analyze topographic maps and aerial photographs*—Historical topographic maps and aerial images contain information about past watershed and channel conditions. Repeated aerial and satellite images can be used to visualize how the channel has changed through time and identify periods of increased rates of bank erosion, which might be associated with large floods or human activities near a bank of concern. Older aerial images can also be acquired through the National Archives. Topographic maps are particularly useful for identifying abrupt changes in slope or valley width, which are locations where bank instability often occurs.

Resources for Preparing WSRA Section 7 Determinations

In addition to the information and associated appendices mentioned above, Appendix 4 provides further resources that are helpful in preparing Section 7 determinations for bank stabilization projects. Appendix 5 provides links to Army Corps general permits from around the country, including details on the permitting process and permitted activities. The list of best practices, required measures, and material specifications for various techniques found in Appendix 4 can be inserted directly into a Section 7 determination to ensure the proposed bank stabilization project is consistent with WSR values.

Conclusions

Lateral migration and bank erosion are natural processes fundamental to building complex, dynamic, and resilient landscapes and creating healthy rivers. National Park Service policies and the Wild and Scenic River Act mandate that river management protects natural hydrologic processes, including lateral migration and associated erosion and deposition, whenever possible. When conflicts between infrastructure or land use and stream processes are unavoidable, WSR and NPS managers must first consider relocating or redesigning facilities rather than manipulating rivers and streams and stabilizing their banks. When bank stabilization is unavoidable, managers are required to use techniques that are visually nonobtrusive and that protect natural processes to the greatest extent practicable (National Park Service 2006). For rivers designated into the National Wild and Scenic River System, the WSRA prohibits federal assistance for water resources projects, such as bank stabilization, that adversely affect a WSR's free-flowing condition, water quality, or outstandingly remarkable values. The unique protections granted to WSR and NPS-managed rivers necessitate that managers consider the unintended and indirect impacts of bank erosion management strategies during the planning process.

If bank stabilization is necessary, early involvement in the bank stabilization design is critical to ensure that bank erosion management is consistent with river ecosystem health, WSR values, and NPS policies. River managers should refer to the overview in *Approaches to Managing Bank Erosion* in the main document and more detailed guidance in Appendix 1 to identify treatments most aligned with NPS and WSR values at a given site. Managers should also use the decision tree outlined in *Selecting an Appropriate Approach to Managing Bank Erosion* to ensure approaches most consistent with WSR values and NPS policies are considered first, with less desirable approaches selected only if favored techniques are unsuitable. Readers are highly encouraged to consult the accompanying appendices, where actionable information about assessing watershed conditions and resources for making Section 7 determinations can be found.

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Appendix 1

This appendix contains factsheets that provide detailed information on the approaches for managing bank erosion and the suitability of each approach for WSR and NPS-managed rivers.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Preserve the erodible corridor.

Visualizing the method:
See Figure 12.

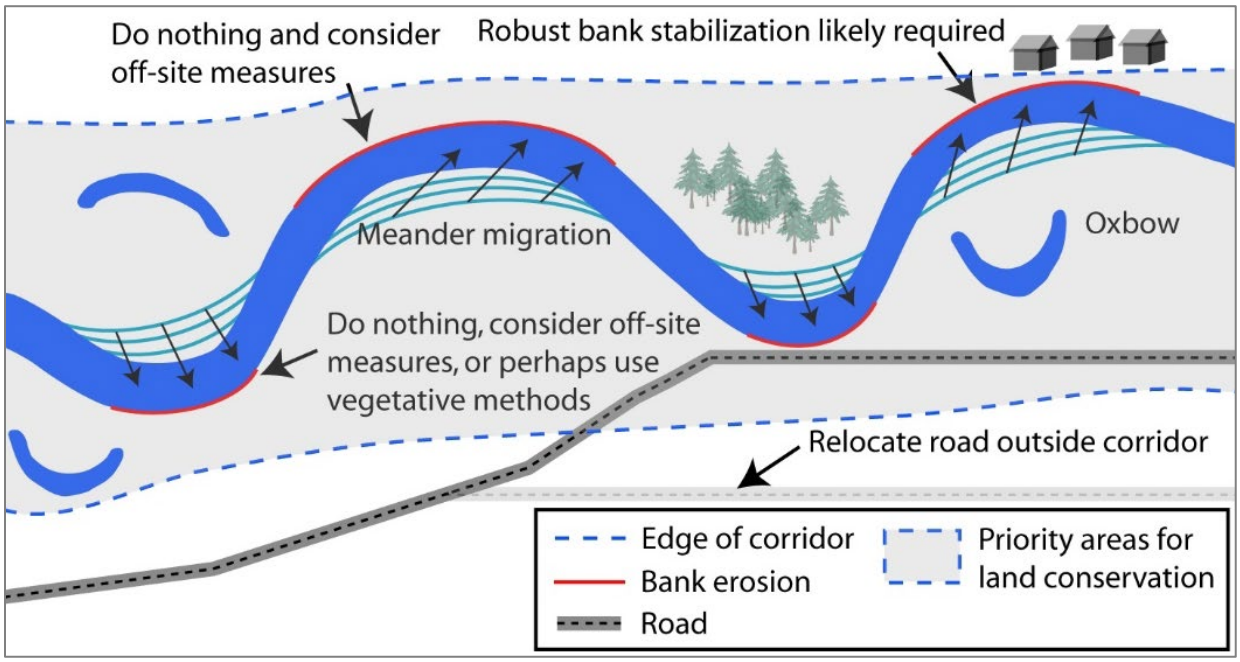


Figure 12. Approach to managing erosion depends on the location, rate, and direction of erosion, with the "Preserve the erodible corridor" or "Do nothing" method recommended where no infrastructure or resources are threatened, even if erosion is just as severe as elsewhere. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Bank erosion is a natural process that allows rivers to adjust to short- and long-term changes in streamflow and sediment delivered by the watershed. Bank erosion occurs in geomorphically, stable, healthy rivers, and natural background levels of bank erosion are important ecologically as bank erosion and point bar development create a patchwork of different habitats that exist in close proximity. Bank stabilization can have undesired secondary impacts that destabilize the river, causing excessive erosion elsewhere that harms aquatic habitat. When the river is responding to a watershed disturbance, adjustments in the rate of lateral shifting and bank erosion allow the river to adapt to new watershed conditions, and bank erosion should be allowed to continue whenever possible. Therefore, the "Preserve the erodible corridor" or "do nothing" options should be

considered first before resorting to bank stabilization techniques that disrupt natural processes. The erodible corridor can be preserved by methods such as land acquisition, conservation easements, and landowner stewardship that can make it easier to do nothing else. Geomorphic assessments are critical to understanding the cause of bank erosion and how bank erosion rates have changed through time. Such information allows river managers to predict how bank erosion might proceed in the future and make informed decisions regarding the need to protect valuable infrastructure or resources and, if needed, how to mitigate potential secondary impacts of bank stabilization projects.

Applicability:
See Figure 13.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
1. Preserve erodible corridor	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 13. Appropriateness of preserve erodible corridor technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 3. NPS

Considerations:

- Undertake a geomorphic assessment by a trained professional to understand how channel will evolve if no action is taken
- Default option should always be to do nothing with reasons given why it is not viable
- Develop a monitoring program to ensure erosion does not cause future conflicts
- $: No construction costs but funds needed for geomorphic assessment and monitoring
- Off-site measures combined with no action if infrastructure is some distance from site
- Relocate infrastructure that is within river corridor and do nothing at erosion site
- Limit stabilization to where infrastructure is outside the corridor and near erosion site
- Erosion must be viewed as a natural self-stabilizing process and not inherently bad

A helpful checklist for reviewing plans:

- Continued erosion at site will not immediately threaten infrastructure.
- If infrastructure is at risk, can it be relocated outside the erosion hazard area?

- Geomorphic assessment has been completed to understand causes of erosion and future trends.
- All stakeholders are satisfied that doing nothing or acquiring land is an acceptable approach.
- A monitoring program has been developed to ensure erosion does not cause future conflicts.
- A funding source has been identified to ensure the monitoring program is sustainable.
- Margins of river corridor have been identified and erosion is within corridor.
- Site access will create significant impacts if bank stabilization is attempted.
- Does the do-nothing approach have potential downstream benefits that reduce erosive forces where infrastructure is present?
- The do-nothing approach averts significant ecological impacts of bank stabilization.
- Off-site measures have also been considered to avoid future bank stabilization at the site.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Off-site measures

Visualizing the method:
See Figure 14.

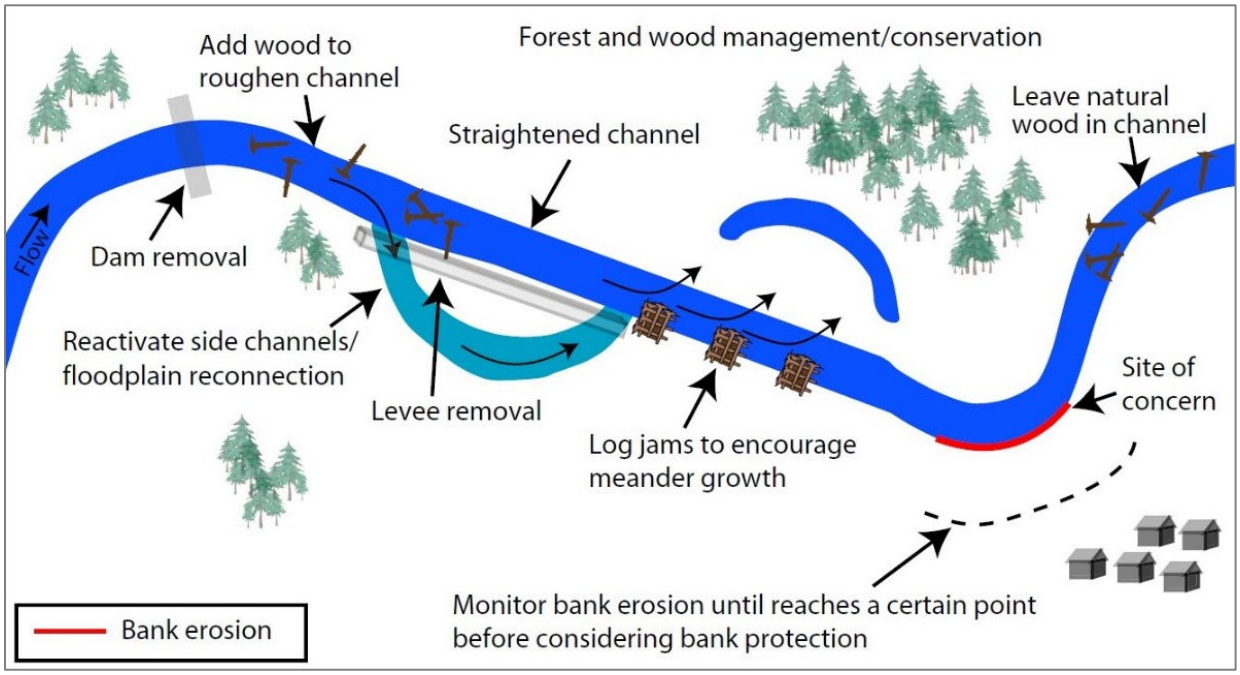


Figure 14. Numerous off-site measures that can be taken to reduce erosive forces at an erosion site. Other possible methods not shown are relocating infrastructure (see Preserve erodible corridor fact sheet), stormwater management, and site runoff controls. NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Off-site measures are projects that can be completed away from the eroding bank to 1) remove the conflict with the river (e.g., road relocation), 2) reduce the erosive forces on the eroding bank (e.g., floodplain reconnection), or 3) remove the need for immediate bank stabilization that impedes ongoing natural processes (e.g., relocate infrastructure). Not all off-site measures can be used at each site (e.g., no side channels may be present) and no such options may be viable at many sites due to jurisdictional/land ownership issues and/or lack of access for heavy machinery. However, investigating the possibility of implementing off-site measures can lead to a better understanding of the causes and severity of bank erosion and whether the erosion is likely to continue.

Applicability:

See Figure 15.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
2. Off-site measures																	
- Watershed management	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
- Relocate infrastructure	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
- Reactivate side channels	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	△	●
- Floodplain reconnection	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	△	●
- Dam removals	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
- Reform meanders	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	△	●
- Increase channel/floodplain roughness	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
△ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 15. Appropriateness of off-site measures for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 4. NPS

Considerations:

- Geomorphic assessment needed to establish link between erosion and off-site measures
- Most off-site measures will be most effective if completed near bank erosion site
- Reactivating side channels often sustainable only if main channel partially obstructed
- $$$: Costs vary with measures used but can be quite high (e.g., dam removal)
- Off-site measures most (cost) effective when multiple erosion sites require work
- Identify other benefits of off-site measures (e.g., improve habitat) to increase viability
- Only consider measures that promote maintaining desired channel processes.

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- The proposed measures are unlikely to create new bank erosion issues elsewhere in the system.
- Landowner permission has been granted to work at off-site locations and access is viable.
- Off-river measures (e.g., remove levee) are preferred over in-channel measures.
- Geomorphic and hydraulics assessment demonstrates that bank erosion is caused by off-site conditions.
- Geomorphic and hydraulic assessment demonstrates proposed actions will reduce erosive forces at site.
- Infrastructure is not imminently threatened or can be relocated, so off-site measures have time to work.
- Multiple off-site measures are considered to improve overall effectiveness of efforts.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Planting vegetation

Visualizing the method:
See Figure 16.

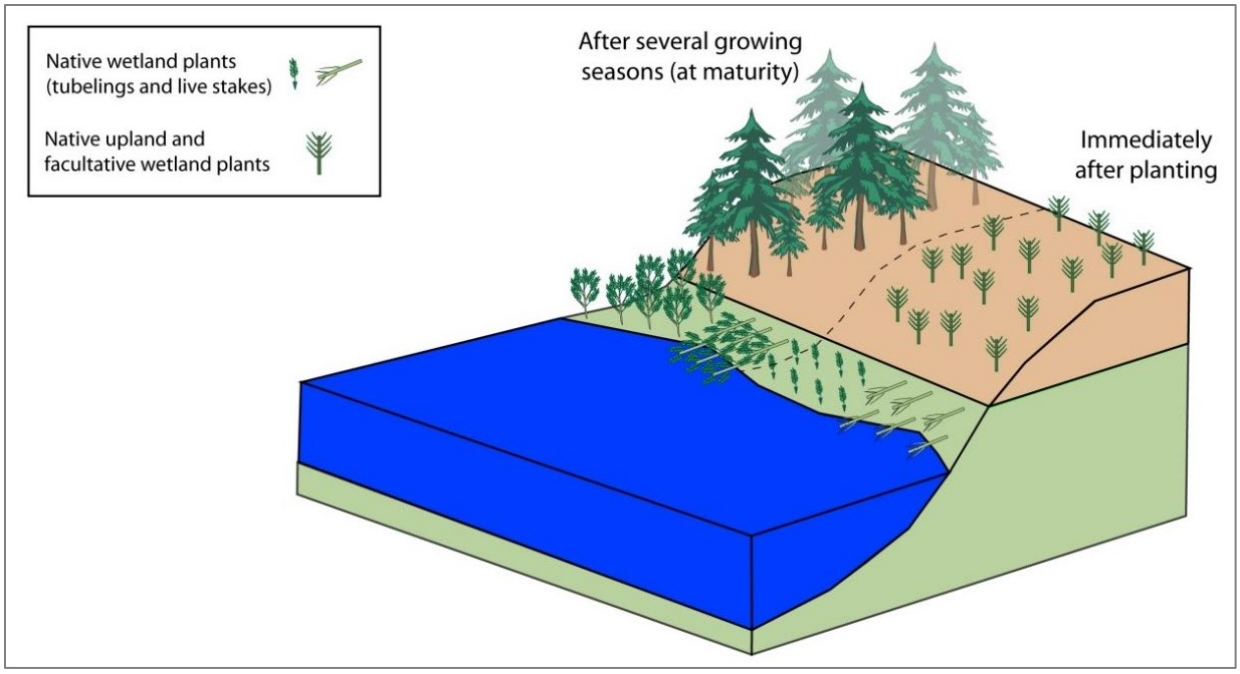


Figure 16. Schematic depicting how vegetation plantings mature through time and promote bank stability. NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Vegetation is a critical element for stabilizing riverbanks in a natural manner. Therefore, planting vegetation (trees, shrubs, grasses, etc.) is an essential element in bank stabilization projects and for ensuring their sustainability. Vegetation cover increases the bank roughness, dissipating near-bank velocity and reducing the susceptibility of bank material to fluvial entrainment while vegetation roots increase bank strength. The types of vegetation to use in bank stabilization projects vary with climate and bank position (i.e., height above the water surface) (see *Native plants* table). Vegetation should consist of water-tolerant plants lower on the bank and more drought-tolerant species used further up the bank slope and on the overbank area where floodwaters may reach only once every year or two. Plantings may be appropriate only on the upper bank if strong erosive forces are experienced on the lower bank or the bank slope is steep (and bank reshaping is not possible). Particular care must be given in (partially) confined settings where flow energy even on the upper bank slopes can be high. Fast growing grasses can also be included in bank stabilization projects to provide more immediate stabilization against low-energy flood flows and gullying by rainfall runoff down the slope, while trees and shrubs have time to mature sufficiently to provide stability on their own. All vegetative treatments, whether using trees, shrubs, or grasses, should be composed of species native to the site of bank stabilization and favor those with the densest and deepest rooting systems. Planting vegetation will often be accompanied with bank reshaping and more robust techniques at the toe of the bank where strong erosive forces are possible.

Applicability:

See Figure 17.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Planting native trees, shrubs, etc.	●	●	▲	●	●	●	▲	●	●	▲	●	●	▲	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 17. Appropriateness of the bank reshaping technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 5. NPS

Considerations:

- Use on lower bank only if erosive forces are very low or no longer active
- Must be combined with other techniques at bank toe if erosive forces remain active
- Use fast growing grasses or brush mattress for immediate bank surface protection
- Use only species native to area where bank stabilization is occurring
- Use water-tolerant species lower on bank and grade upward to dry-tolerant species on the upper bank and overbank areas.
- Potted plants should be removed from pots and roots loosened before planting
- $: Relatively inexpensive, but 100% survival is rare, so budget for replanting
- Planting during dormancy causes less stress and leads to better plant survival

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Plantings include only species native to area and are locally sourced (see *Native plants* table).
- Plantings are restricted to upper bank or low-energy environments.
- Short-term stabilization treatments (grasses, brush mattress) are included so plants can mature.
- The bank slope is appropriate for plantings or bank reshaping is planned.
- Plantings are zoned from lower wet-tolerant to higher drought-tolerant species.
- There is a plan in place to monitor plant survivability and budget for replacement plants.

- Details are provided on removing plants from containers and loosening roots.
- Plantings are scheduled for when plants are dormant.
- Plants selected are consistent with the site soil type (alluvial vs. nonalluvial soils).
- Other methods are considered that complement planting vegetation.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Live stakes

Visualizing the method:
See Figure 18.

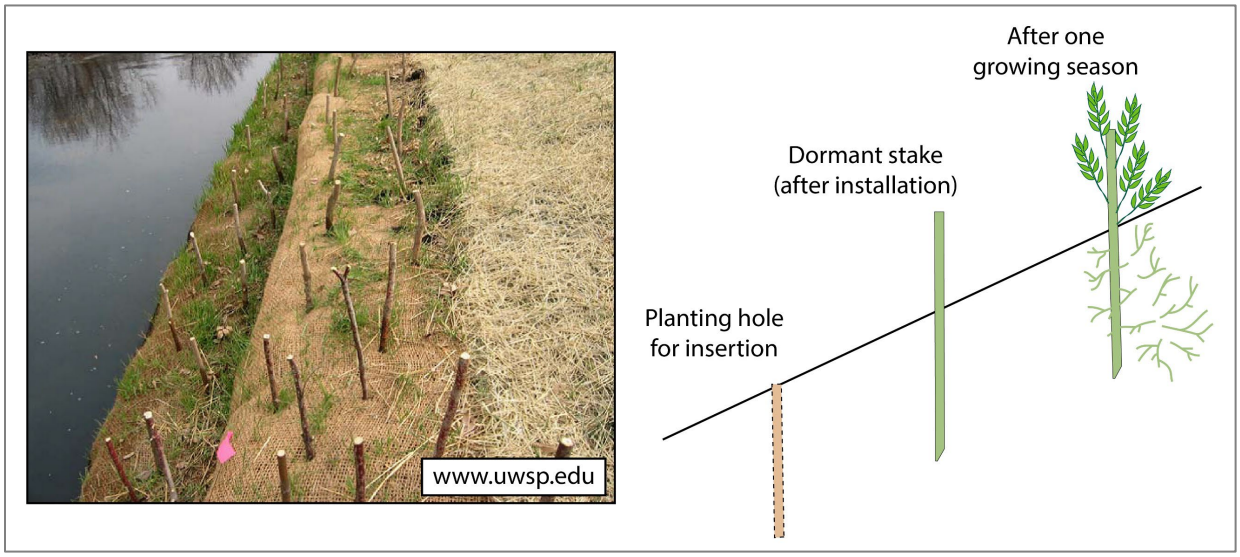
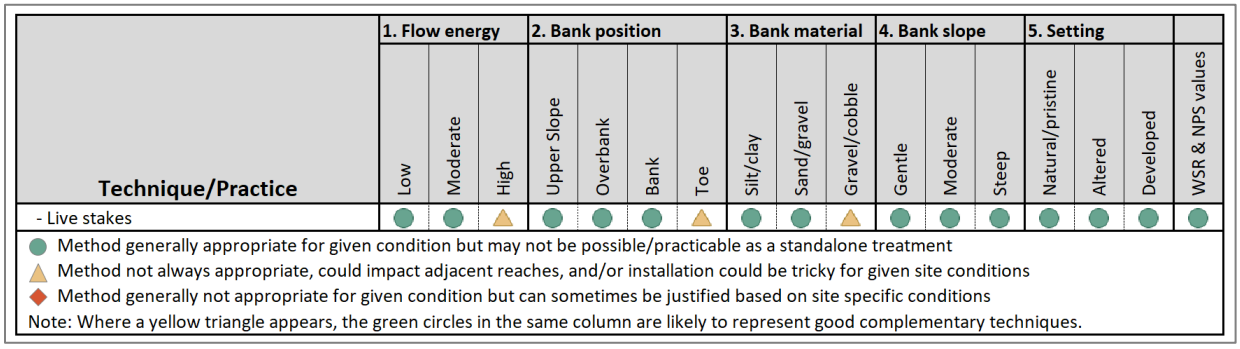


Figure 18. Field example of live stake planting and schematic showing how live stake planting matures through time. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Many trees and shrubs will take root when a dormant stem cut from a live plant is partially buried in the soil. An inexpensive method to stabilize an eroding bank is to insert numerous such stems (referred to as live stakes) into the (reshaped) bank. Hundreds of such stakes can generally be gathered near the site where vegetation is naturally growing along the river. Smaller diameter stems (i.e., < 2") can be cut with a point at their base to ease insertion in the bank soil. Rebar or waterjet stingers can be used to create a starter hole in firmer soils and machine-mounted steel rams used to form deeper holes for large-diameter stems (i.e., > 6"). Live stakes grow best if cut stems are inserted upright into the banks, so marking their proper orientation during transport is important if not otherwise obvious. Live staking is appropriate for low-energy environments and works best on the lower bank where the cut stems are in contact with the water table or capillary fringe; live stakes in dry regions have little chance of sprouting if not reaching the capillary fringe. Since live stakes do

not provide much surface protection until leafed out the following growing season, this method is best combined with other treatments such as brush mattresses or fascine bundles. Appropriate native species to use by region for live stakes are provided on the *Native plants* table.

Applicability:
See Figure 19.



Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Live stakes	●	●	▲	●	●	●	▲	●	●	▲	●	●	●	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 19. Appropriateness of live staking technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 6. NPS

Considerations:

- Use in low-energy settings only and place low on bank so plants are the near water table for moisture.
- Stakes should be harvested when dormant with base recut and soaked in water prior to installation if not used immediately
- Cut stakes with basal point to ease insertion; use rebar/steel ram to form holes in firm soils
- Bury ½ to ⅔ of stake in bank soil with stakes typically 6 to 12 inches in length; plant upright
- Combine with brush mattresses and fascine bundles to increase surface coverage
- $: Low cost when done by hand but machine can be used with steel ram to insert larger diameter (> 6") stakes
- Space stakes 2 to 3 feet apart in several offset rows to maximize coverage of bank surface
- Use live stakes for anchoring erosion control fabrics or fascine bundles rather than plastic or manufactured wooden stakes

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- Method suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).

- Spacing between stakes is appropriate and rows are offset.
- Stems are inserted upright and a method for marking orientation during transit is described.
- Bank material is characterized and the proposed method of insertion is appropriate.
- At least half of the stake length is buried in the bank soil.
- Live stake diameter is sufficient if being used to anchor fascines or other treatments.
- Appropriate native species are used that can sprout (see *Native plants* table).
- Stakes are harvested when dormant, and bases recut and soaked in water if not used quickly.
- Live stakes are placed low enough on bank to ensure sufficient soil moisture.
- Erosive forces have been characterized and are low enough for stake diameter proposed.
- Other methods are considered that complement live staking approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Fascine bundles

Visualizing the method:
See Figure 20.

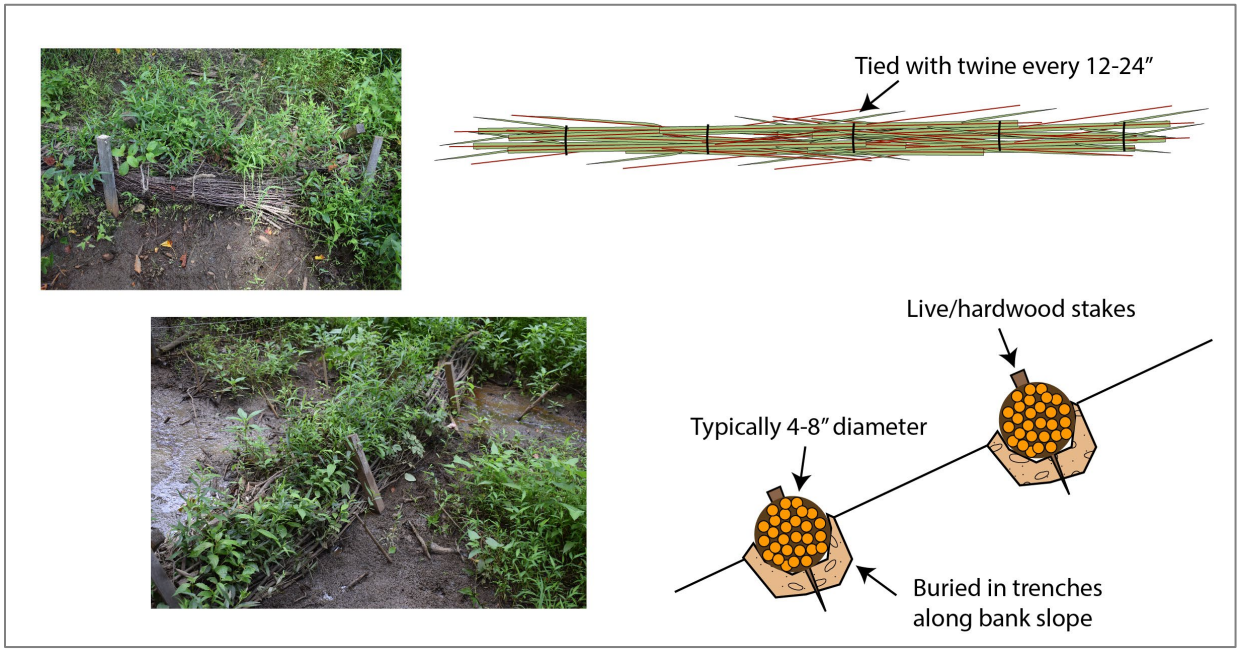


Figure 20. Field photos of fascine bundles and schematic showing how fascine bundles are installed.
NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Fascine bundles are a vegetative technique that consist of branches harvested from live trees that are bundled together into a long tube shape; the long bundles consist of shorter groupings of branch cuttings that overlap at their ends and are lashed together with twine or other biodegradable material. Fascines serve to limit gullying of the bank surface (particularly unburied inert bundles), create roughness on the bank surface that limits the erosive forces acting on the bank soils, and establish riparian habitat quickly (when live stems are used). Live fascines have the added benefit of generating roots that bind the soil together and top growth that provides added surface protection and habitat. The fascine bundles, once assembled, are placed in multiple, generally evenly spaced, rows on the bank parallel to the water's edge, and anchored in place with (live) stakes. Fascine bundles can be "live" so they will root and leaf out over time but can also be inert with no later growth expected. Live fascines should be placed in a shallow trench such that most but not all of the fascine is buried when backfilled to ensure the bundles have good contact with the surrounding soil, which is especially important if live fascines are to sprout.

Applicability:

See Figure 21.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Fascine bundles	●	●	▲	●	●	●	▲	●	●	▲	●	●	▲	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 21. Appropriateness of fascine bundle technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 7. NPS

Considerations:

- Live fascines best placed lower on bank where better soil moisture will assist regeneration
- Branches used should be harvested just shortly before construction, so don't dry out
- Use branches > 6' long and 0.25" to 2" in diameter to form bundles 12" to 18" in diameter
- Not appropriate on steep banks (> 2:1 slope) with non-cohesive soils
- $: Low cost when completed by hand but machines ok when needed for other activities
- Can be combined with brush mattresses for better surface coverage

- Consider species but use at least a 3' spacing between rows on steep banks (1:1 slope) and up to 8' on gentler 4:1 slopes
- Useful for trapping fine sediment that can further enhance vegetative growth

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- Method suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Rows are parallel to water surface with inert bundles higher on slope with low soil moisture.
- Spacing between rows of fascines is appropriate for bank slope and soil cohesiveness.
- Trenching by hand, if required, is possible and resources are available to do so.
- Live stakes are used for anchoring or, if not, stakes aren't expected to survive (i.e., no moisture).
- Live fascines include appropriate native species that can sprout (see *Native plants* table).
- Branches are harvested just before construction and the duration of construction is estimated.
- Total fascine length has been estimated, and a nearby source for branches has been identified.
- There is an area identified on site to assemble fascine bundles.
- Orientation of the base and top within live bundles alternates for better vegetative coverage.
- Other methods are considered that complement fascine bundles (e.g., brush mattresses).
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Brush mattresses

Visualizing the method:
See Figure 22.

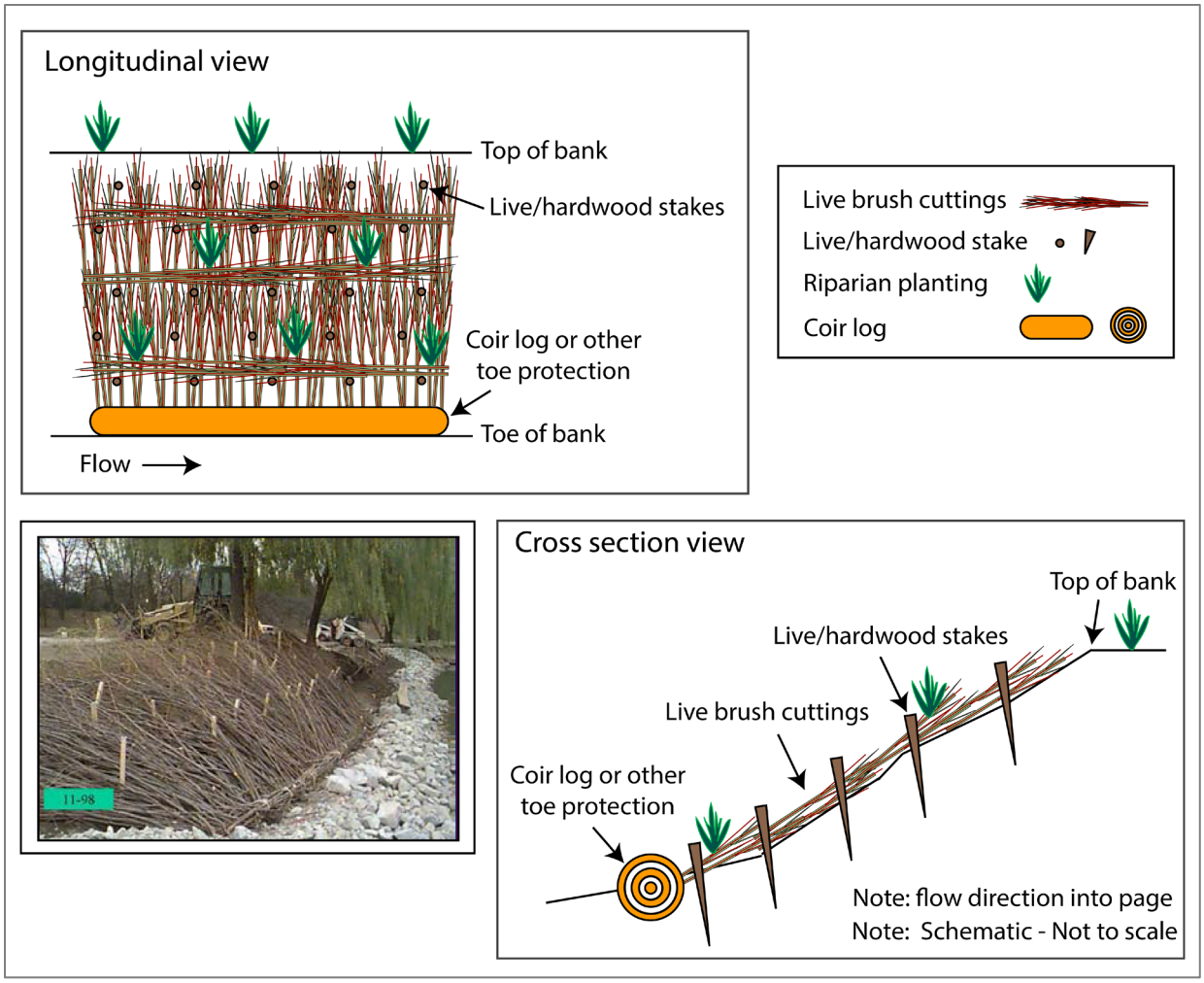


Figure 22. Schematic depicting how brush mattresses are installed and field photo showing brush mattresses after installation. SCHEMATIC—NPS / FIELD GEOLOGY SERVICES, LLC; PHOTO—NATURAL RESOURCES CONSERVATION SERVICE

Description:

Brush mattresses are a vegetative technique that covers the bank surface with long branches and twigs that are typically anchored to the bank with live wooden stakes. The mattresses create roughness on the bank that reduces the erosive force of flowing water, protecting the bank material from fluvial erosion. Long branches are stacked horizontally and vertically in a crisscross fashion on the bank face and additional materials are interwoven to increase stability. Brush mattresses are generally used in concert with other techniques such as live stakes, plantings, bank reshaping, fascine bundles, and, where forces are strong, more robust measures at the bank toe such as log crib walls or engineered log jams.

Applicability:

See Figure 23.

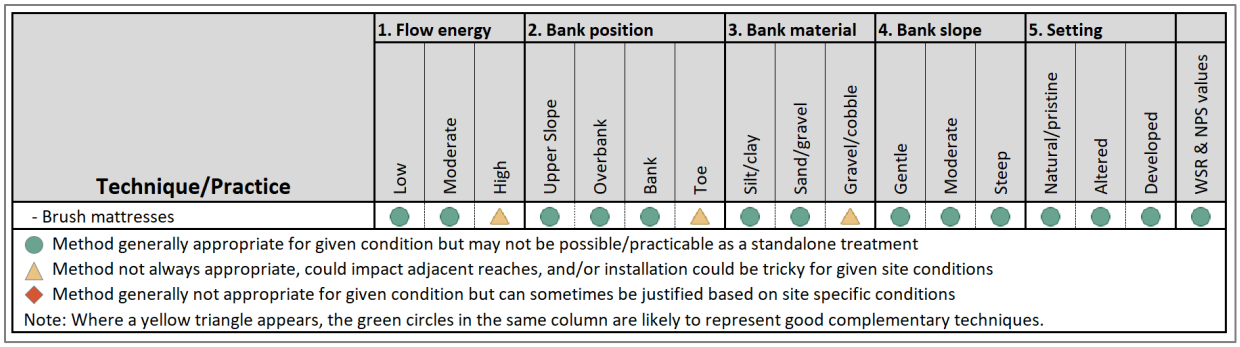


Figure 23. Appropriateness of brush mattresses technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 8. NPS

Considerations:

- Not to be used below typical base flow level as interplanted vegetation will not survive
- Branches used should be harvested just shortly before construction, so not brittle
- Certain species if slightly buried in soil could take root and revegetate bank surface
- $: Relatively inexpensive but labor-intensive when done by hand
- Place largest branches lower on bank surface where erosive forces highest
- Can be completed by hand if needed due to difficult or problematic machine access
- Mainly intended for short-term protection while riparian vegetation matures
- Useful for trapping fine sediment that can further enhance vegetative growth

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/protect land" option has been ruled out.
- Method suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Open spaces between branches are minimal.
- There are no large gaps in treatment along length of the eroding bank.
- Bank material has been characterized and stakes can be hammered into bank.
- Live stakes are preferred for anchoring.
- Native rot-resistant species are used (see *Tree species vs. rot resistance* table).
- Branches are harvested just before construction and the duration of construction has been estimated.
- Treatment is placed above typical base flow and outside of high-energy areas.

- Largest branches are placed lower on bank.
- Branches interwoven and oriented in multiple directions.
- Other methods are considered that complement the brush mattress approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Hydroseeding and Mulching

Visualizing the method:
See Figure 24.



Figure 24. Field photos showing hydroseeding on a bank directly after installation. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Hydroseeding is a technique that is used to control erosion, stabilize slopes, and speed vegetative growth on disturbed areas at construction sites. Hydroseeding mixes consist of seed, mulch, and water that are blended into a slurry and then sprayed onto disturbed areas. Some mixes also include tackifiers, fertilizers, and dye. Tackifiers (binders) are used to strengthen bonds among fibers within the hydroseed mix and to increase adhesion to the soil. While fertilizers provide nutrients for plant growth and promote vigor, they can negatively impact water quality. Dye can make it easier to see the where the mix has been applied.

Mulching is used to retain soil moisture, promote seed germination, and reduce weeds. Mulch may be used to support seedlings, container plants, live stakes, and other vegetative planting methods, or it may be applied after broadcasting seed to retain soil moisture. When combined with hydroseeding

it can increase seed germination rates and accelerate plant growth. Mulch is often but not always composed of organic materials.

For hydroseeding applications on streambanks and in riparian areas, biodegradable and non-toxic mulch fibers and tackifiers are favored. Mulch should be at least 50 percent wood fiber; paper mulches and polymeric emulsion blends should not be used. Seed mixes should be native and not contain invasive species. Hydraulic mulch and tackifiers should not be applied below the base flow elevation. Hydroseed should not be applied to areas where water levels are expected to rise prior to germination.

Applicability:
See Figure 25.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Hydroseeding and mulching	●	●	▲	●	●	●	◆	●	●	◆	●	●	▲	●	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 25. Appropriateness of hydroseeding and mulching on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 9. NPS

Considerations:

- Use biodegradable, non-toxic mulch fibers (at least 50% wood fiber) and tackifiers.
- Use only species native to area where bank stabilization is occurring.
- Use fast-growing grasses and forbs for immediate bank surface protection. Include woody species for longer protection.
- Apply below common flood elevation only if erosive forces are very low or no longer active.
- Avoid paper mulches and polymeric emulsion blends.
- Avoid hydroseeding during dry seasons to maximize germination and promote growth.
- Combine with other vegetative planting methods such as live stakes and container or balled and burlapped shrubs and trees.
- Use water-tolerant species at lower bank positions and transition to dry-tolerant species on the overbank and upper slope.

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- The slope is appropriate for hydroseeding, or bank reshaping is planned.
- Only biodegradable and non-toxic materials (with at least 50% wood fiber) are used for much fibers and tackifiers
- Paper mulches and polymeric emulsion blends are not used.
- Seed mixes include only species native to area and are locally sourced (see *Native plants* table).
- Specified species transition upward with bank position from water-tolerant to drought-tolerant.
- Application is restricted to overbank and upper slope positions or low-energy environments.
- Long-term stabilization treatments (woody shrubs and trees) are included so more complex vegetative communities can become established.
- Hydroseeding is scheduled to maximize germination and promote plant growth.
- Other methods are considered that complement planting vegetation.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Log crib walls

Visualizing the method:
See Figure 26.

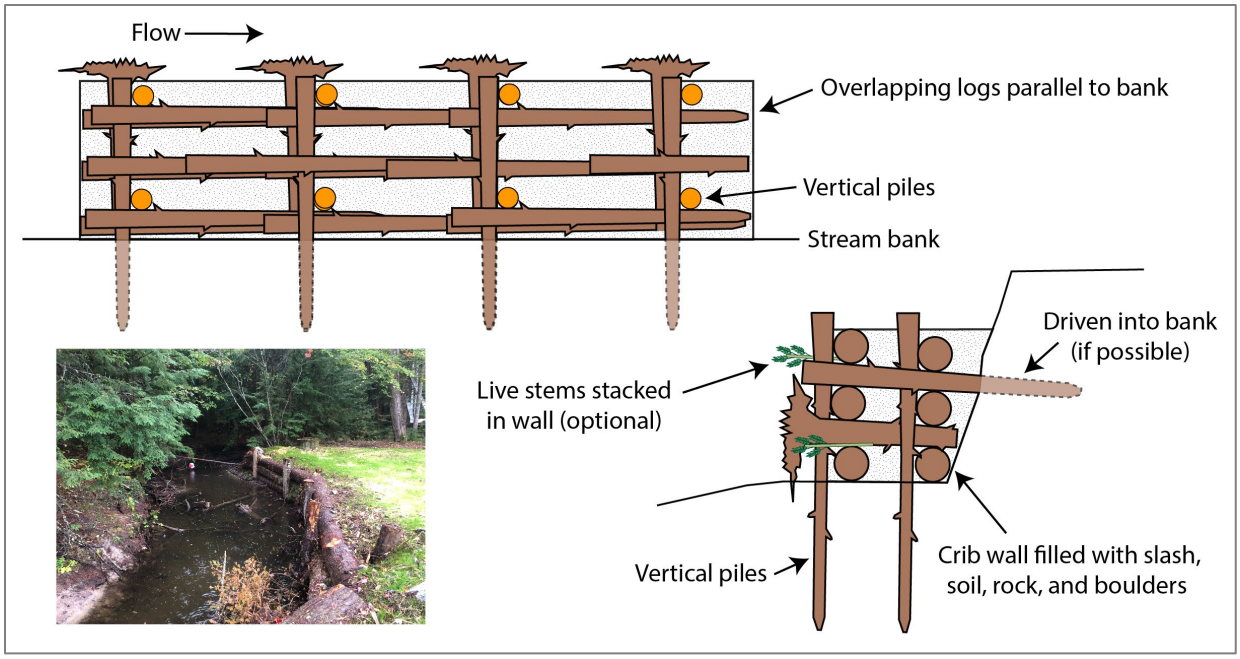


Figure 26. Schematic depicting log crib wall installation and a field photo of log crib wall installed on a bank. PHOTO—© CUMBERLAND COUNTY SOIL AND WATER CONSERVATION DISTRICT / CHRISTOPHER BALDWIN; SCHEMATIC—NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Log crib walls are a surface treatment that covers the lower portion of the bank (where erosive forces are highest) and are anchored in place with vertical pile logs. Logs are stacked in alternating directions with long logs used parallel to the flow and shorter logs perpendicular to the flow (unless longer logs can be driven easily into the bank). Log crib walls are typically continuous structures that run the full length of the eroding bank. The upper slope above the crib wall can be treated with vegetative techniques, such as brush mattresses, fascine bundles, live stakes, or plantings. The open space between the crib logs is typically infilled with slash (i.e., brush, leaves, branches) and some soil, rock, and boulders for ballast. Cabling or bolting to the pile logs may be required based on buoyancy and drag force calculations to ensure the structure is sufficiently anchored to resist the erosive forces at the site, but these anchoring methods should be avoided if possible and only used on the top logs. If calculations determine that cabling is needed, the structure should be cabled in separate units so the logs can disassemble in case of failure. Cabling to boulders can be considered where driving log piles may prove difficult.

Applicability:

See Figure 27.

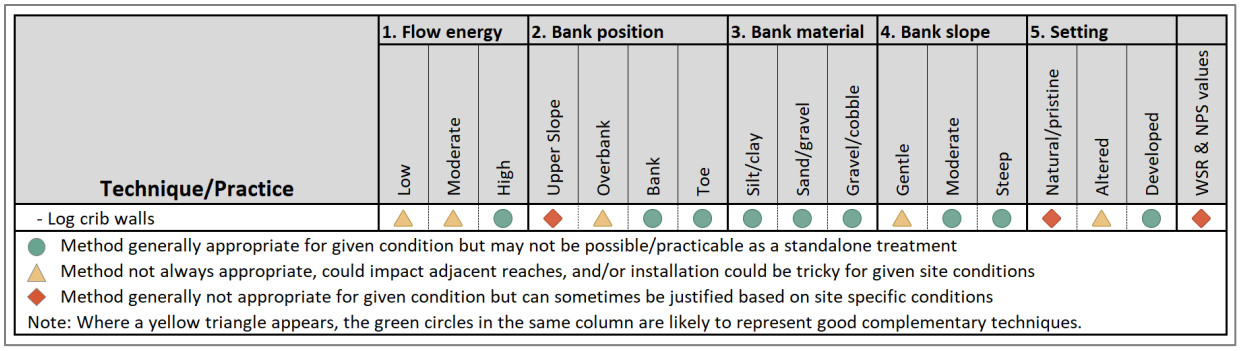


Figure 27. Appropriateness of log crib wall technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 10. NPS

Considerations:

- Crib walls are good on narrow channels as they do not extend into the channel like log jams
- Boulders can infill the log cribbing for ballast where sensitive infrastructure is very close to bank
- Crib walls built to full bank height or alternate technique needed for upper bank in partly-confined and confined valley settings.
- $$$: High cost for materials and heavy machinery; machines need access to site
- Live stems can be planted in soil between layers of logs
- Use larger logs higher in structure to reduce buoyancy forces and provide ballast
- Anchoring using vertical piles is best, so knowing substrate conditions is important
- Use native rot-resistant species to extend functional life for decades

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- If crib wall extents into the channel, it does so only minimally (i.e., <10% of channel width).
- Boulders are used for ballast if sensitive infrastructure is near bank or very high erosive forces are present.
- Alternative anchoring techniques are identified in case of difficulty driving vertical piles.
- Rot-resistant species are used (see *Tree species vs. rot resistance* table).
- Slash and tree tops of rot-resistant species are available to infill open space in crib walls.

- Native species of live stems are interplanted between log layers (see *Native plants* table).
- Crib wall will be built to the bank height or extend to the upper bank in partly confined and confined valley settings.
- Logs with largest diameter are above design flow elevation to provide ballast.
- Anchoring is done without cables, or cables are minimal and obscured as much as possible.
- Other methods are considered that complement the log crib wall approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Tree revetments

Visualizing the method:
See Figure 28.

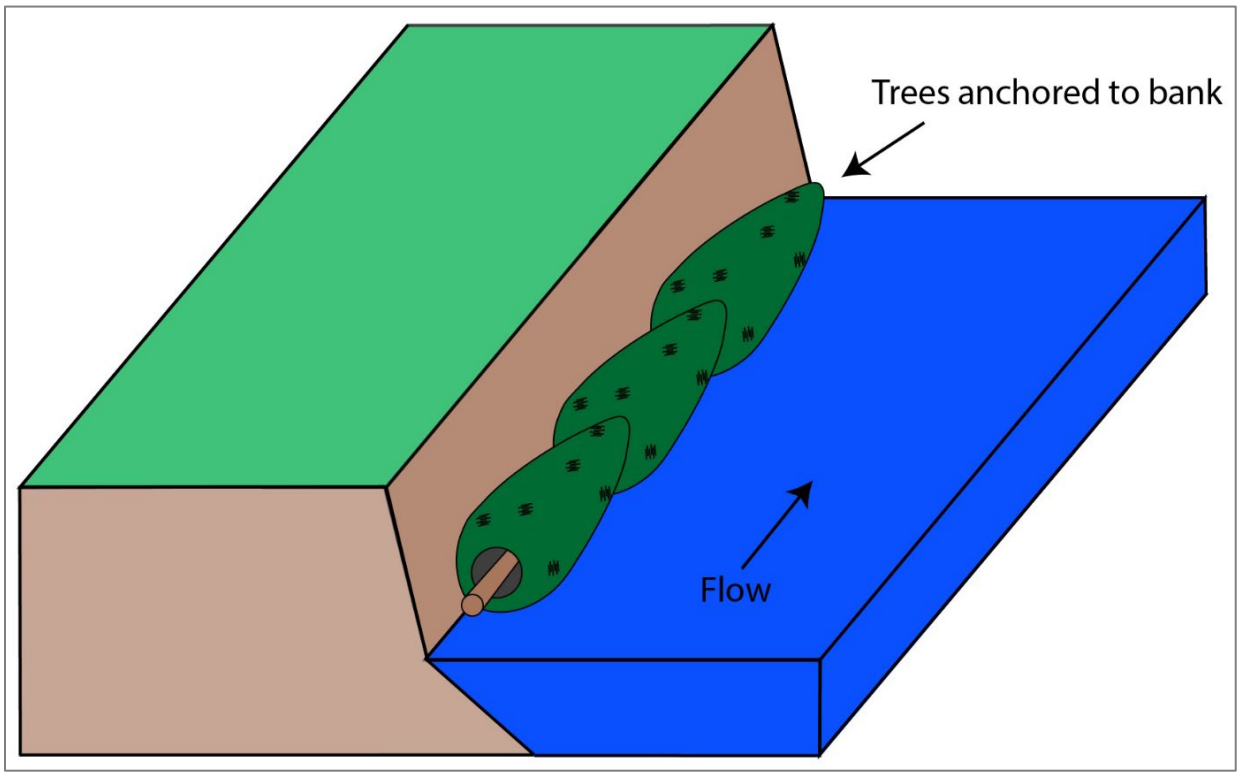


Figure 28. Schematic depicting tree revetment installation and field photo of tree revetment installation on a bank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Tree revetments are a surface treatment that covers the lower portion of the bank with slightly overlapping (often coniferous) trees laid parallel to the bank. Usually, the upper half of the tree with the dense network of branches is used, which reduces the weight and size of the trees that need to be

maneuvered into place by hand, but revetments with whole trees including root wads can be constructed with heavy machinery. The branches (and roots when used) create roughness along the bank that reduces the near-bank flow velocity, promoting sediment deposition. The branches also help trap sediment sloughing off the upper bank. Cedar trees work particularly well given their dense network of branches and rot resistance. Tree revetments are traditionally anchored in place with cable and earth anchors, but this approach creates potential recreational hazards and is inconsistent with WSR values and NPS policies. An alternative is to use biodegradable cordage with earth anchors or to pin the trees with log posts driven horizontally into the banks and vertically in the bed. The bank posts should touch the upstream face of the bed posts, and two sets of posts should be used for each tree. The posts can be installed with a sledgehammer where fine-grained sediments are present or with a pneumatic post driver in somewhat coarser sediments.

Applicability:
See Figure 29.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Tree revetments	●	▲	▲	◆	▲	●	●	●	●	●	●	●	●	▲	●	●	▲

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 29. Appropriateness of tree revetment technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 11. NPS

Considerations:

- Two layers of trees with one stacked on top of another can be used on higher banks
- $$: Can be completed by hand on smaller streams with work crews to reduce costs
- Place basal layer of trees such that they extend below the low-flow water line
- Use where banks and beds are composed of fine-grained sediment for ease of anchoring
- Trees must be handled with care to prevent branches from breaking off
- Orient root wad or butt end of tree upstream with upstream tree overlapping to the outside
- Can be installed against steep banks with only minor disturbance /no bank reshaping needed
- Use rot-resistant species with dense networks of branches

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Vegetative techniques are planned for higher on the bank if tree revetment protects only lower portion of the bank.
- Fine-grained sediment is present if construction is to be completed by hand.
- Erosive forces lower on the bank are low or pile logs are used for anchoring.
- Alternative anchoring techniques are identified in case of difficulty with planned approach.
- Rot-resistant species with dense branches are used (see *Tree species vs. rot resistance* table).
- Transport and construction techniques will minimize loss of branches.
- Basal layer is partially submerged below the low-flow water level.
- Root wad or butt ends of trees are oriented upstream with >10% overlap with adjacent trees.
- Other methods are considered that complement the root revetment.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Root revetments

Visualizing the method:
See Figure 30.

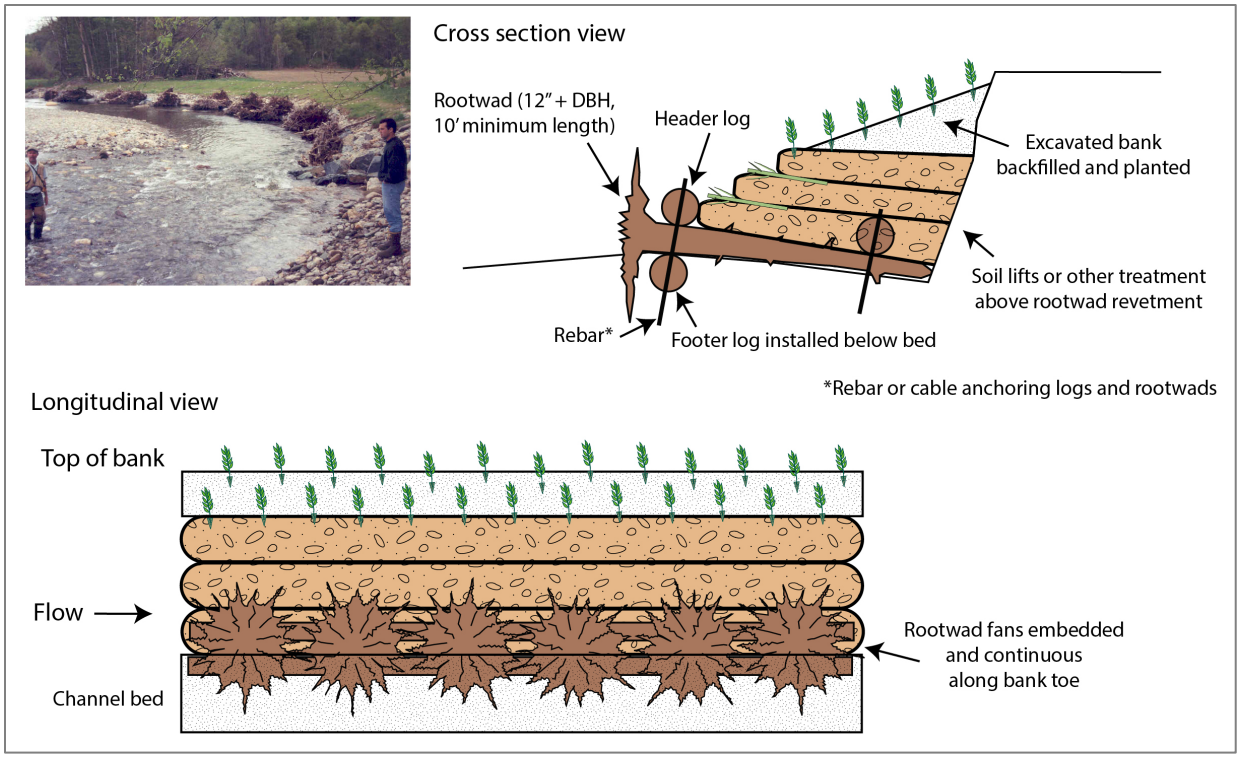


Figure 30. Schematic depicting root revetment installation and field photo of root revetment installation on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Root revetments are a surface treatment that covers the lower portion of the bank (where erosive forces are highest) with root wads with an attached length of log for anchoring. The roots create roughness that reduces the near-bank flow velocity, induces deposition, and creates cover habitat. Native rot-resistant species with large-diameter root fans should be used (see *tables Appendix 1.a and 1.b* and consult a local forester). If the bank is being reconstructed, the root wads can be anchored by burying the attached logs in sediment as the bank is built up to its full height. To minimize disturbance of native soils, root wad logs can be driven into the bank toe. Alternatively, footer and header logs laid parallel to the bank can span and hold in place several roots without bank excavation. The header logs can then be anchored to vertical log piles or boulders (using rope). Where erosive forces are low, rebar passing through the header, footer, and root wad logs and into the channel bed below is an anchoring alternative. In all cases drag force and buoyancy calculations should be completed to ensure an adequate Factor of Safety is built into the design, especially where critical infrastructure is present.

Applicability:

See Figure 31.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Root revetments	●	●	▲	◆	▲	▲	●	●	●	●	●	●	●	▲	●	●	▲

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 31. Appropriateness of root revetment technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 12. NPS

Considerations:

- Select trees with large-diameter root fans
- $$: Treatment restricted to lower bank but additional costs for upper bank treatment
- Bottom of root wad may need to be slightly buried in channel bed for log to lay flat
- If bank is composed of fine sediment, logs can be pushed into bank for anchoring
- Use rot-resistant durable species native to the region
- Root wads should be as flush to the bank surface as possible
- Can support base of a reconstructed bank or be installed on undisturbed banks
- Effective in high-velocity environments when well-anchored

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques planned higher on the bank where bank is above the height of root wads.
- Fine-grained sediment is present if roots are anchored by pushing logs into the bank.
- Erosive forces lower on the bank are low or adequate anchoring details are provided.
- Alternative anchoring techniques are identified in case of difficulty with planned approach.
- Rot-resistant and durable species are used (see *tables 2 and 3 in Appendix 1*).
- Transport and construction techniques will preserve full diameter of root wad.
- Base of roots is buried below channel bed to ensure log lays flat at bed level.
- Adequate number of root wads are purchased to treat project length.

- Other methods are considered that complement the root revetment approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Bank reshaping

Visualizing the method:
See Figure 32.

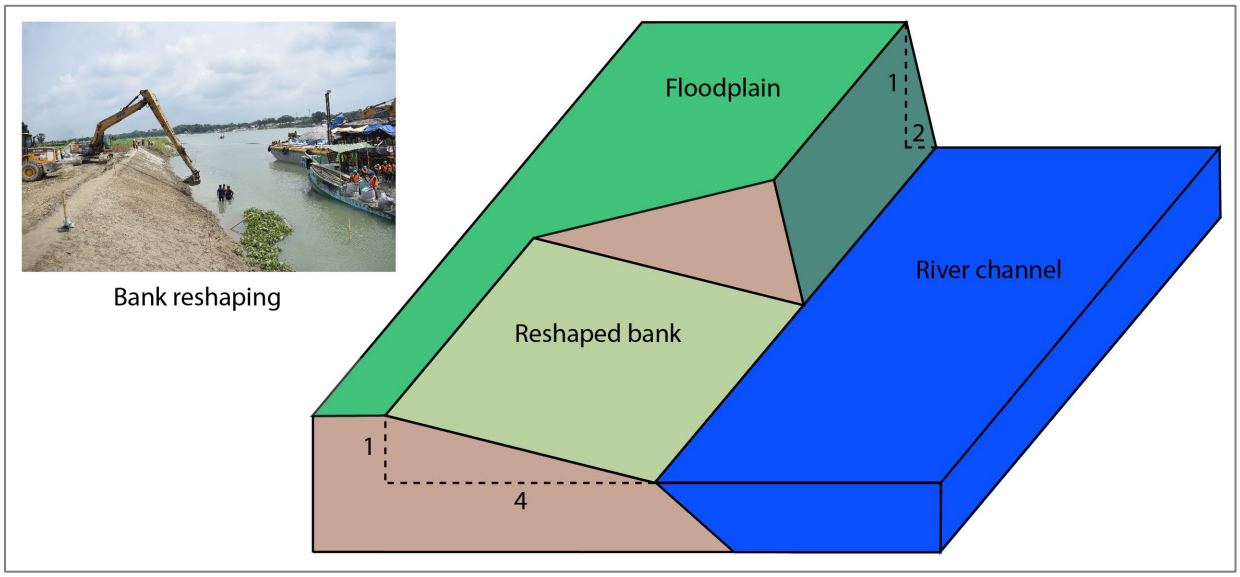


Figure 32. Schematic depicting the process of bank reshaping and field photo of a reshaped bank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Bank reshaping is used to "lay back" a moderate or steep eroding bank, enabling planting or placement of other vegetative treatments (e.g., live stakes, brush mattresses, fascine bundles) on a gentler slope. Bank reshaping mimics how a bank would naturally re-stabilize once erosive forces are no longer impinging on the bank toe, allowing material sloughing from the top of the bank to accumulate at the base without being swept away by the river's flow. If the erosive forces continue to act at the toe, bank reshaping must be accompanied with other stabilization techniques that ensure the bank toe does not continue to erode. The reshaped bank surface must be treated with vegetative stabilization techniques to protect the exposed soil from becoming rilled and gullied by heavy rain and surface runoff. Sufficient space must also be available for bank reshaping as the top of the bank will move landward to reduce the bank slope. On higher banks, the bank may need to shift a considerable distance landward to achieve a gentle slope. Bank reshaping usually creates between a 4:1 and 2:1 (horizontal:vertical) slope (i.e., near the angle of repose depending on the material) with anything gentler requiring the bank to be moved too far landward, creating an unnatural look, while anything steeper risks failure unless proper techniques are used (e.g., fabric-encapsulated soil lifts).

Applicability:
See Figure 33.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Bank reshaping	●	●	▲	●	●	●	●	●	●	●	◆	▲	●	▲	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 33. Appropriateness of the bank reshaping technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 13. NPS

Considerations:

- Use on lower bank only if erosive forces are very low or no longer active
- $: relatively low cost as a standalone option but must be combined with other techniques
- Use with vegetative techniques to cover bank surface to prevent gullying and weeds
- Sufficient space must be available to shift the top of bank landward for bank reshaping
- Reshape bank to lower slope in less cohesive soils prone to collapse (e.g., sands)
- Upper portion of bank can be reshaped, while the steeper lower bank is stabilized differently
- Mainly intended to provide a lower gradient slope on which to plant riparian vegetation
- Heavy machinery needed given the typically large earth-moving requirements

A helpful checklist for reviewing plans using this technique:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Bank reshaping is inappropriate if removal of mature trees is required.
- Bank reshaping is restricted to bank or very low-energy environments.
- Proposed bank slope is consistent with naturally stable banks of the same composition.
- Appropriate native species (see *Native plants* table) are used on the reshaped bank.
- Bank toe is treated with another technique if strong erosive forces are still present.

- Reshaped bank surface is treated with vegetative techniques to prevent gullying.
- Excess soil from reshaping is appropriately reused or removed from the site.
- Sufficient space is available for the top of bank to shift landward the required distance.
- Other methods are considered that complement bank reshaping (e.g., planting vegetation).
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Fabric-encapsulated soil lifts

Visualizing the method:
See Figure 34.

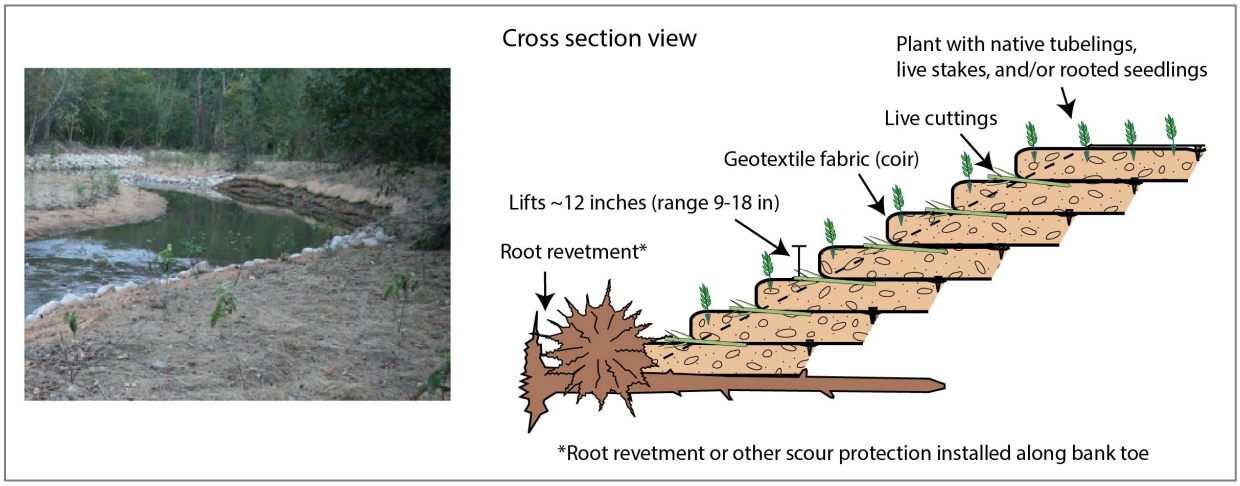


Figure 34. Schematic depicting fabric-encapsulated soil lift installation and field photo of fabric-encapsulated soil lifts on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Fabric-encapsulated soil lifts (a.k.a. vegetated geolifts, soil lifts, or FES) are a deformable treatment consisting of vertically stacked layers of soil wrapped in fabric (preferably biodegradable, such as coir) with stems of live cuttings laid down between (and through the exposed top portion of) each layer for subsequent sprouting and rooting. Soil lifts are designed to withstand design flows for several years, so the bank remains stable until the vegetation planted between individual lifts matures and provides sufficient root strength to withstand fluvial erosive forces. Soil lifts are an excellent treatment for lower on the bank above the bank toe where treatments that can withstand stronger erosive forces are present (e.g., log jams, log crib walls). Vegetative treatments (e.g., plantings, live stakes) should be used higher on the bank, above the soil lifts. Since lifts can be built nearly vertically, they are useful where space is limited and where the bank needs to be reconstructed at a steep slope using only soil. Soil lifts provide an excellent complement to deformable treatments at the bank toe (e.g., coir logs, biodegradable rock bags) such that natural bank and channel processes can eventually reemerge after the forces causing the erosion have been addressed with off-site

measures (e.g., reconnection to floodplain, reactivation of side channels) or are no longer present at the site.

Applicability:
See Figure 35.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Fabric-encapsulated soil lifts	●	●	▲	▲	●	●	▲	●	●	◆	▲	●	●	▲	●	●	▲

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 35. Appropriateness of fabric-encapsulated soil lift technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 14. NPS

Considerations:

- Use biodegradable fabric to ensure natural aesthetic returns over the long term
- $$: While materials are inexpensive, the construction process is labor-intensive
- Do not use at toe of bank where erosive forces are typically highest and very strong
- Pull fabric surrounding soil taut and anchor with wooden (even live) stakes; batter boards can help support vertical lift faces
- Orient stems perpendicular to bank in between lifts with tips extending out past lifts
- Useful where space is limited as multiple soil lifts can be stacked nearly vertically
- Lifts are generally 1-foot thick and extend back from base of bank a minimum of 3 ft
- As long as successive layers are stepped back 3 to 5 feet, lifts can protect banks 20+ ft high

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques are planned for bank toe if erosive forces are too high for soil lifts.
- Scour mitigation measures are considered, especially where fine-grained sediment is present.
- Live cuttings are used between each soil lift in the proper orientation.

- Thickness, set back distance, and distance into bank for the soil lifts are appropriate.
- Biodegradable fabric is being used and a method for securing it tightly is detailed in plans.
- Soil in the soil lifts is from on-site source or is certified to be free of invasive plant seeds.
- Fabric overlaps if the width of the fabric rolls is less than the project length.
- Sufficient construction oversight is planned to ensure lifts are taut.
- Other methods are considered for the bank toe and upper bank that complement soil lifts.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Rock/sand bags

Visualizing the method:
See Figure 36.

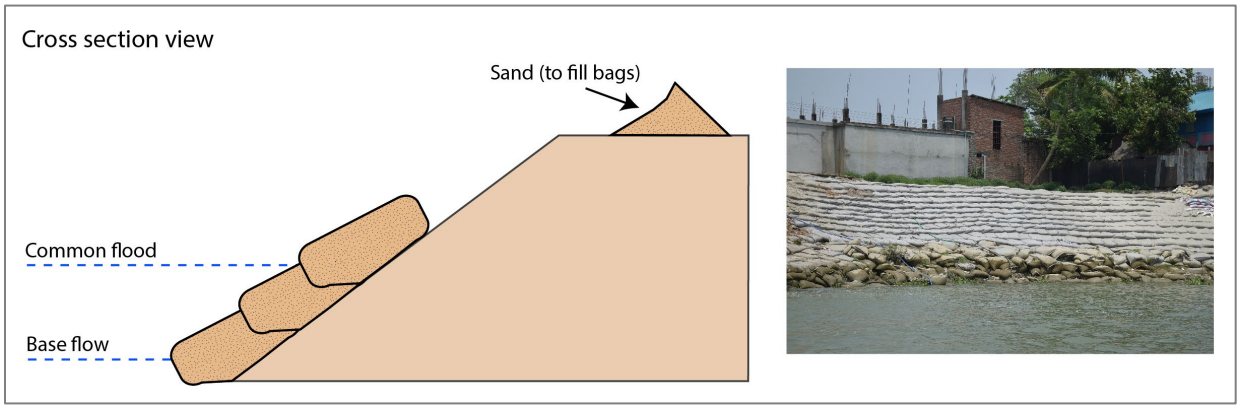


Figure 36. Schematic depicting rock and sand bag installation and field photo of sand bag installation on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Rock- or sand-filled bags are better known for mitigating flood inundation but can also be used as a deformable bank stabilization treatment when the bags are stacked against the face of an eroding bank. The bags, preferably biodegradable, may be appropriate in an emergency as they are easy to deploy. The bags can also persist for several years, providing time for vegetation planted between the bags (and into the soil behind) to mature and develop a root system that is strong enough to withstand the erosive forces of flowing water. Rock or sand bags are flexible enough to settle into scour holes without a loss in project function and are easier to install than fabric-encapsulated soil lifts. When confined to the bank toe, biodegradable bags filled with coarse native substrate (gravel/cobble) can be used to create a deformable bank toe that provides intermediate stability while bio-engineered treatments on the bank become established. After the bags decompose, the native substrate is released into the river with minimal, if any, impact. This approach, as well as other deformable bank treatments, are thus more consistent with WSR values than other stabilization approaches. Similar,

self-hardening sand bags (a mix of sand, concrete, and small stones) do not biodegrade, are not as flexible, and should not be used in WSR settings. Since the rock/sand bags can be stacked against nearly vertical banks, they are useful where bank reshaping is not an option.

Applicability:
See Figure 37.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Rock/sand bags	△	●	△	◆	◆	△	△	△	△	△	△	●	●	◆	●	●	△

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
△ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 37. Appropriateness of rock and sand bag technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 15. NPS

Considerations:

- Use bags with biodegradable fabric to ensure natural aesthetic returns over time
- $: Materials are inexpensive and bags can generally be filled and placed by hand
- Use at bank toe as a deformable treatment even where erosive forces fairly high
- Do not anchor bags, so they can settle and fall into scour holes that develop
- Place live stem cuttings in between bags and ensure they extend into native bank soil
- Useful where space is limited as bags can be stacked nearly vertically
- Lay bags on bank or do not stack more than 4 ft high if they are to stand alone
- Rivers with lots of floating wood or ice can puncture sand bags so use sturdy materials

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- The method is used as a deformable treatment at bank toe or on the bank during an emergency repair.
- Sand bags laid against the bank are less than 4 ft high if intended to stand alone.

- Live cuttings planned for use between bags are long enough to extend into native soil.
- Bags are not anchored, so they can settle and fall into emerging scour holes.
- Biodegradable fabrics are used, and the stacking method is detailed in the plans.
- Fill material is from an on-site source or certified to be free of invasive plant seeds.
- Stockpile of sand bags and fill materials are available if intended for emergency preparedness.
- Bags are sturdy enough to resist puncturing by wood and ice floating down river.
- Other methods are considered above the bank toe that complement the rock/sand bag approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Coir logs

Visualizing the method:
See Figure 38.

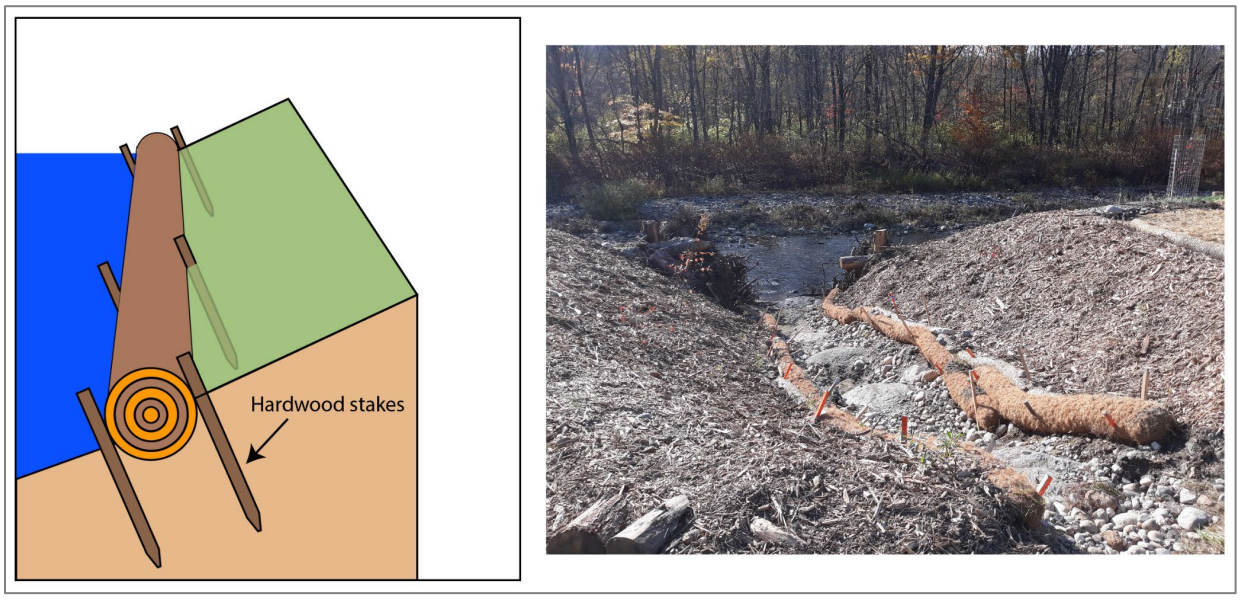


Figure 38. Schematic depicting coir log installation and field photo of coir log installation on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Coir logs are a deformable treatment that will decompose over several years but give time for plantings or live stakes to mature and provide longer-term stability. Coir logs consist of tightly compressed biodegradable coconut fibers shaped into long, flexible cylindrical rolls that are anchored with (live) wooden stakes. Typically, a single log is placed along the bank toe of small low-energy

streams but can be stacked 2 or 3 logs high; however, higher stacks become unstable. Coir logs should be placed in a trench with the lower half buried below grade to protect against minor scour. The logs are typically 1-foot in diameter and come in lengths of 10 or 20 feet that can be tied together to treat longer lengths of bank. Coir logs can be used on the bank in a manner similar to fascine bundles in order to prevent erosion from slope runoff, trap sediment, and support plant growth. Since coir logs decompose over time, this treatment must be combined with other stabilization methods (most often vegetative treatments). Coir logs are compact and water retention is less than loamy soils, so plantings survive better when placed immediately upslope from coir logs rather than through the coir logs themselves. Live cuttings extending into the bank can also be placed over the top of the coir logs.

Applicability:
See Figure 39.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Coir logs	●	▲	▲	●	●	▲	▲	●	●	▲	▲	●	●	▲	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 39. Appropriateness of coir log technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 16. NPS

Considerations:

- Coir logs are not natural looking but quickly obscured by vegetation growth
- $: Funds needed to purchase coir logs but relatively easy to install by hand
- Use at base of bank only where erosive forces are low
- Wedge logs between offset wooden stakes as driving stakes through logs is difficult
- Place live stakes upslope of logs as planting into them is difficult and less successful
- Logs can be bound together along length of bank but typically only 1 log high (3 max)
- Set top of coir logs at an elevation where proposed plantings can take hold.
- Coir logs create smooth bank lines with limited roughness and associated habitat

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques are planned for the bank toe if erosive forces are too high for coir logs.
- Coir logs are stacked only 1 log high or ample justification given to go up to 3 logs high.
- Live cuttings are planned above logs or methods for creating holes in logs are specified.
- Logs are wedged into offset stakes for anchoring and stakes can be readily inserted in bed.
- Correct number of logs is planned, supplier is identified, and a method to connect logs is detailed.
- Coir logs are set at an elevation on the bank where proposed plantings are suitable.
- Actions are identified to ensure coir logs look natural and provide near bank habitat.
- Volunteers or large enough labor force is planned for installation.
- The base of the coir logs will be partially buried at base of bank.
- Other methods are considered that complement the coir log approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Erosion control blankets and fabrics

Visualizing the method:
See Figure 40.



Figure 40. Field photo of erosion control blankets immediately after installation (left) and one year after installation (right). © INTERFLUVE / MARTY MELCHIOR

Description:
Erosion control blankets and fabrics are a deformable treatment that covers the bank surface with a thin layer of biodegradable or synthetic material and are designed to withstand the expected erosive forces of flowing water, so vegetative treatments have time to mature. The blankets and fabrics come in long spools up to 15 ft wide that are unrolled over and staked down to the eroding or reshaped bank surface. The multitude of materials (e.g., coir fiber, straw, plastics) and styles (e.g., mesh opening size, thickness) available commercially are designed for different purposes which are often not intended for riverine settings. Laboratory tests show some fabrics can withstand strong erosive forces. Regardless, these fabrics should only be used where erosive forces are low to moderate (e.g., bank and overbank area) with other more robust treatments needed in higher energy settings (e.g., bank toe). Only woven and mechanically bound biodegradable fabrics should be considered on NPS-managed rivers and WSR settings, because other fabric types compromise the natural aesthetic and plastic netting and welded joint matting can be lethal to reptiles.

Applicability:
See Figure 41.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			WSR & NPS values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	
- Erosion control blankets and fabrics	●	▲	▲	●	●	▲	◆	●	●	◆	●	●	●	▲	●	●	●

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 41. Appropriateness of erosion control blanket and fabric technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 17. NPS

Considerations:

- $$: Cost of commercial product and labor-intensive to install; use only biodegradable fabrics to limit biotic and aesthetic impact
- Place fabric down slope rather than across slope so ends buried in soil or other treatment (e.g., tree revetment, coir logs)
- Use at base of bank only where erosive forces are low as fabrics tend to bunch up
- To prevent erosion underneath fabric, ensure good soil to fabric contact when installing
- Use biodegradable or live stakes spaced no more than 1.5 ft apart to keep fabric flush with bank
- Overlap different fabric rolls by at least 6 inches to avoid unprotected surfaces

- The open mesh network of some fabrics can cause small wildlife to become entangled
- Do not use pre-seeded blankets to avoid introducing non-native species

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for conditions at the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques are planned for the bank toe if erosive forces too high for fabrics.
- Only biodegradable fabrics and stakes are used.
- Fabric rolls are sufficiently overlapped and spacing of stakes is appropriate.
- Planting plan is provided, and only native plants are used (see *Native plants* table).
- Selected fabric is chosen with some thought towards aesthetic appearance.
- Ample fabric budgeted to cover treatment area.
- Fabric is placed down the slope so ends can be buried in soil or toe treatment.
- Volunteers or large enough labor force is planned for installation.
- Other methods are considered that complement the erosion control fabric approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Rock revetments

Visualizing the method:
See Figure 42.

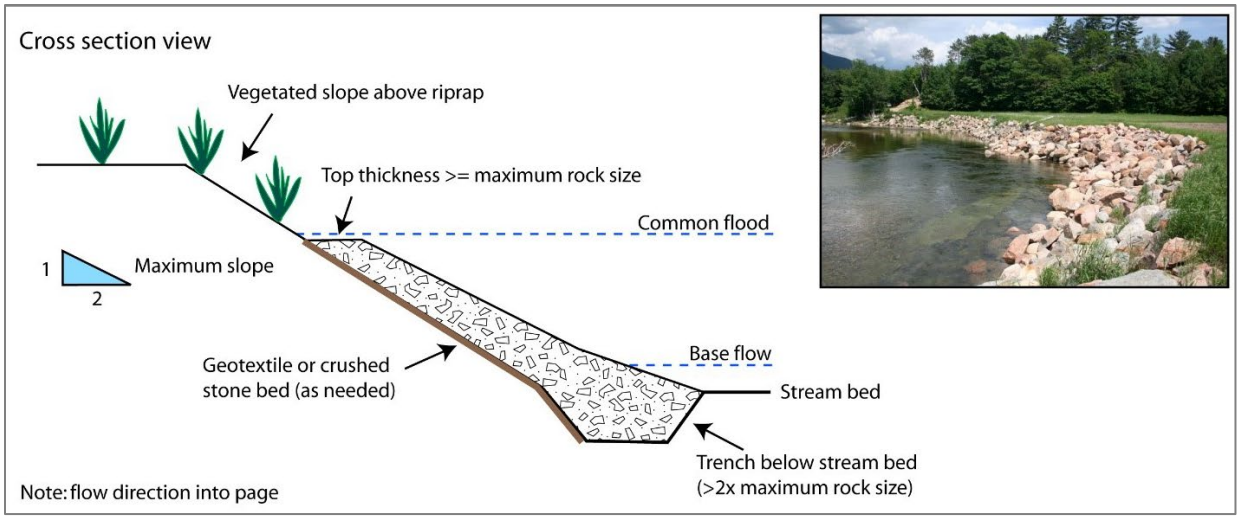


Figure 42. Schematic depicting rock revetment installation and field photo of rock revetment on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Rock revetment (i.e., riprap) is a hard armoring technique that covers the bank toe and the lower portion of the bank with rock sized to withstand movement during the design flood. Rock revetments need to be set below the maximum scour depth or launching aprons used (i.e., extra rock placed at base of bank to fill emerging scour holes) to prevent near bank scour. Rock revetments are inconsistent with Wild and Scenic River values; these structures degrade habitat and are inconsistent with important geomorphic processes by fully arresting erosion while also creating an unnatural aesthetic. Rock revetments should be used only for scour protection around bridge abutments or other valuable infrastructure near the river's edge where erosive forces are high. Using sub-angular to sub-rounded local boulders (with an engineer's specified gradation of different rock sizes for better armoring), interplanting native riparian vegetation between the rocks, and restricting rock use to only the bank below the elevation of the common flood can reduce the negative impacts of rock revetments where no other viable treatment methods are available. Sub-angular to sub-rounded stone is more easily dislodged, so a larger stone size should be used compared to more standard angular/blocky riprap. Voids among the rocks can be choked with native streambed materials. Interplanting of the revetment should be restricted to low-growing shrubs as tall trees with dense root networks can damage revetments if uprooted by strong winds or other causes.

Applicability:

See Figure 43.

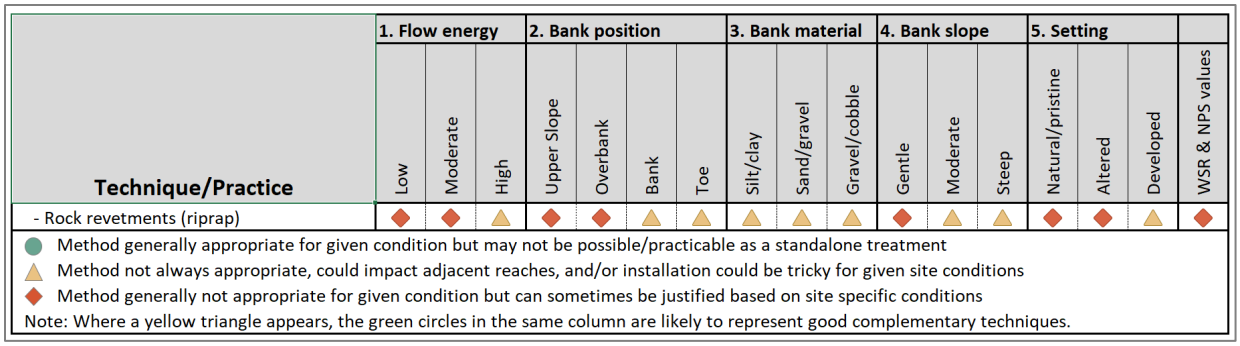


Figure 43. Appropriateness of rock revetment technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 18. NPS

Considerations:

- Use sub-angular to sub-rounded rocks to improve natural aesthetic
- $$: Cost can be reduced by restricting treatment to bank toe with vegetation above
- Expect severe scour on adjacent channel bed and banks where fine sediment present
- Set basal rocks below anticipated scour depth or use launching apron
- Use only below ordinary high water mark (OHWM) and where erosive forces high
- Interplant appropriate riparian vegetation in between rock to improve aesthetic and habitat
- Try to avoid using, especially where banks remain unstable further downstream
- Thickness of revetment should be at least 3 times the average diameter of the rocks used

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- There is no other suitable option (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques are planned for the bank to limit the use of riprap.
- Scour mitigation measures are considered, especially where fine-grained sediment present.
- Sufficient rock is placed on the launching apron to protect against the expected scour depth.
- Rock size is appropriate for erosive forces during design flood and accounts for rock shape.
- The thickness of the revetment is appropriate for the rock size used.
- Other techniques more consistent with WSR values are inappropriate at the site.
- Voids below the common flood elevation are choked with native streambed materials.
- Design considers interplanting or other actions for more consistency with WSR values.

- Banks downstream are stable or unlikely to be destabilized by use of riprap upstream.
- Other methods considered that can be used instead of the rock revetment approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Retaining walls

Visualizing the method:
See Figure 44.

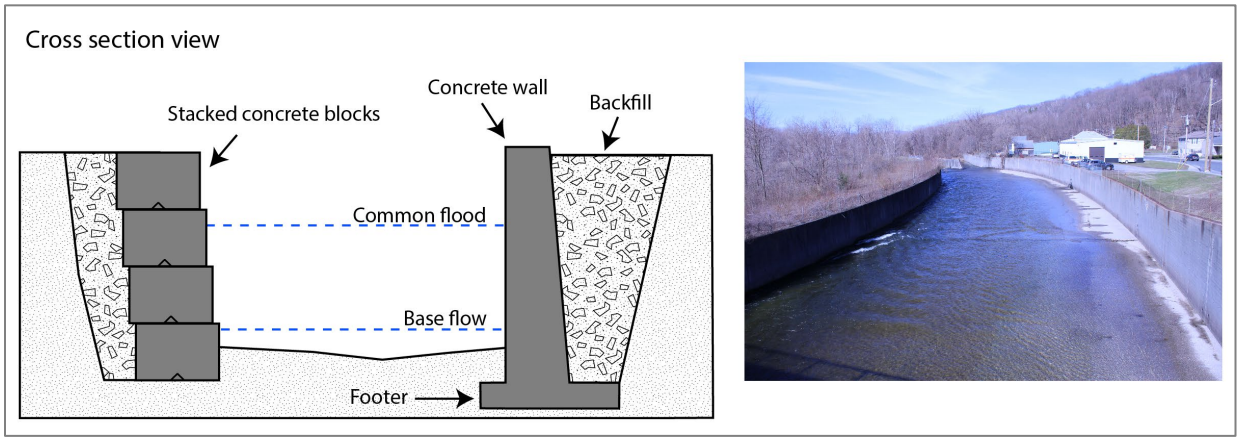


Figure 44. Schematic depicting retaining wall installation and field photo of retaining walls on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Retaining walls are a hard armoring technique generally built with large rock or concrete (blocks), but sheetpile, soil-filled geocells, hewn wood timbers, and gabion baskets filled with cobbles can also be used. The hardened bank can cause near bank scour, which can undermine the wall and shift the flow towards the bank. Retaining walls need to be set below the channel bed or boulders should be placed in front of the wall to serve as a launching apron (i.e., rock to fall into emerging scour holes) to prevent undermining. Retaining walls are inconsistent with WSR values and NPS policies because they degrade habitat, halt important geomorphic processes, and alter the natural aesthetic. Retaining walls should be considered only on steeper slopes where erosive forces are extremely high, deformable techniques suitable for steep slopes (e.g., fabric-encapsulated soil lifts) are unlikely to be effective, and there is limited space to lay back the bank slope. Furthermore, other alternatives such as the relocation of critical infrastructure further from the bank should be given serious consideration before resorting to retaining walls. The use of natural rock or a vegetated geocell wall can reduce the negative impacts of retaining walls when no other viable treatments are available.

Applicability:
See Figure 45.

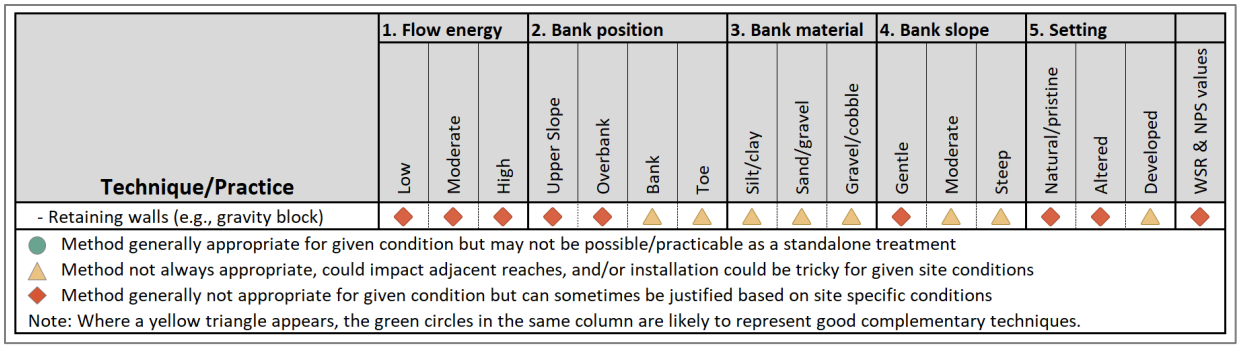


Figure 45. Appropriateness of retaining wall technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 19. NPS

Considerations:

- Use natural rock or vegetated geocells to improve natural aesthetic
- $$$: Retaining walls are generally very expensive to design and construct
- Expect severe scour on adjacent channel bed and banks where fine sediment present
- Set base of wall below expected scour depth during design flood
- Use only where limitations in space and slope rule out use of other options
- Drain pipes through wall needed to relieve hydrostatic pressures
- Try to avoid using, especially where banks remain unstable further downstream
- If space available, use vegetative treatment on upper bank and limit wall to lower bank

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- There is no other suitable option (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Other techniques are planned for higher on the bank to limit height of wall if space is available.
- Scour mitigation measures are considered, especially where fine-grained sediment present.
- Sufficient rock is added at base of wall to protect against expected scour depth.
- Wall design is appropriate for erosive forces during the design flood.
- Each component of the wall (i.e., rock size) is sufficient to withstand motion at the design flows.
- The design considers planted geocells or natural rock to better align with WSR values.

- Downstream banks are stable or unlikely to be destabilized by the retaining wall.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Engineered marginal log jams

Visualizing the method:
See Figure 46.

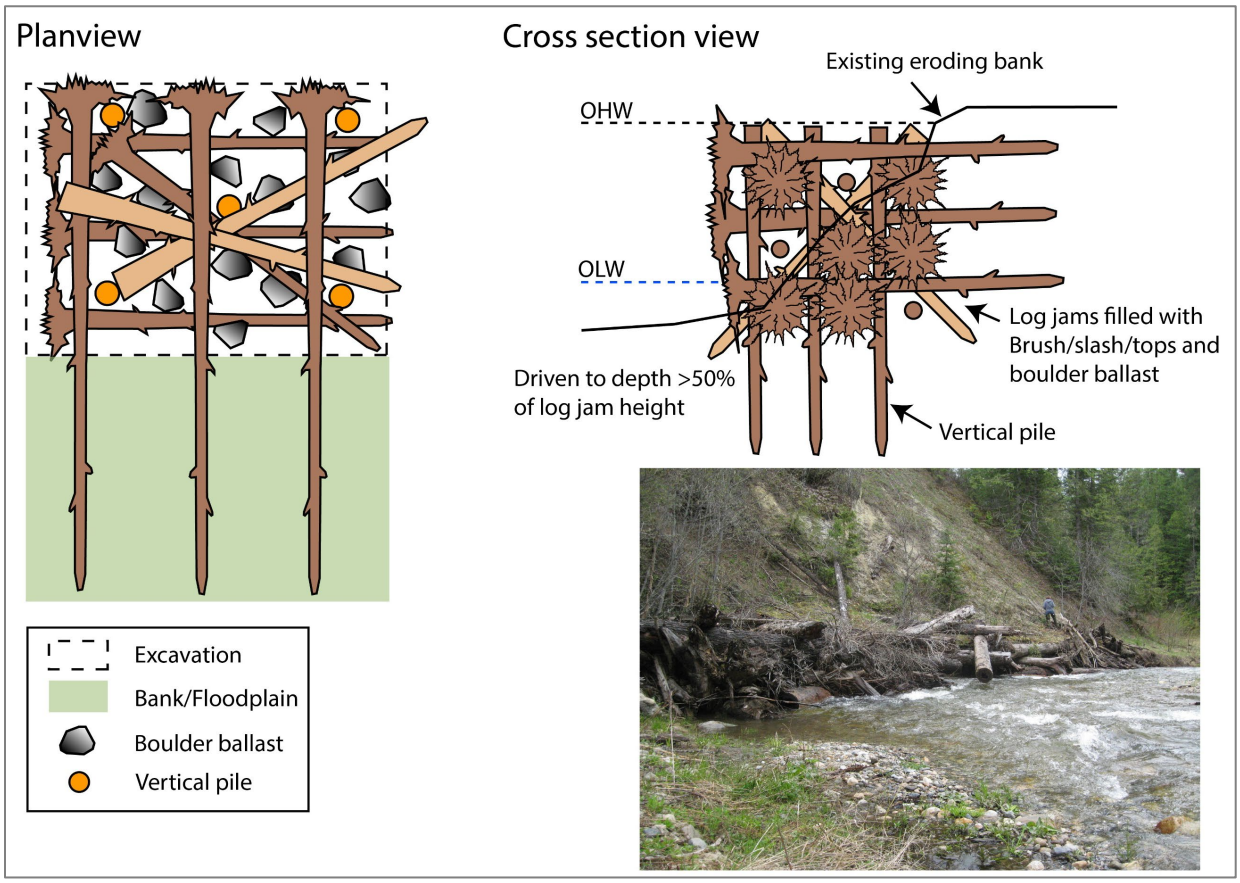


Figure 46. Schematic depicting engineered marginal log jam installation and field photo of an engineered marginal log jam on a riverbank. SCHEMATIC—NPS / FIELD GEOLOGY SERVICES, LLC; PHOTO—© INTERFLUVE / MARTY MELCHIOR

Description:
Engineered marginal log jams are a flow deflection technique mimicking natural features found along the banks of rivers with (partially) forested watersheds. Log jams are built with interlocking logs infilled with slash (i.e., brush, leaves, branches) and lesser amounts of soil, rock, and boulders for ballast. Logs don't need to be stacked in a crib-like fashion. Instead, logs passing through the entire structure diagonally provide better bracing and mimic more random natural accumulations. Log jams are ideally anchored in place with vertical and horizontal log piles with more than half the log length driven into the bed and banks where possible with no artificial anchoring or rock ballast.

In some circumstances, bolting or lashing the top layer of logs to the pile logs or large boulders may be required to ensure log jams remain immobile, depending on the embedment length and local site conditions. Several log jams built in series along the bank are needed for effective stabilization, and deposition is expected to occur in between the jams.

Applicability:
See Figure 47.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Engineered marginal log jams	△	△	△	◆	◆	●	●	●	●	●	△	●	●	△	●	●	△

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
△ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 47. Appropriateness of engineered marginal log jam technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 20. NPS

Considerations:

- Jams should protrude < ⅓ channel's width to prevent impacts to opposite bank
- Distance between jams should be 3 to 5 times the distance jams protrude into river to prevent erosion between structures
- Build jams to full bank height or higher than opposite bank on tall banks
- $$$: Heavy machinery and large trees typically needed, so costs can be very high
- Best for use on wide channels where an unvegetated bar is present across channel
- Good cover habitat and flow complexity created; soil can be placed on top of jams and planted with native vegetation
- Anchoring using vertical piles is best, so knowing substrate conditions important
- Use rot-resistant species to extend functional life for decades

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Log jams protrude < ⅓ of the channel's width.

- The log jam spacing is appropriate for the channel size (i.e., 3 to 5 times protrusion length).
- Alternative anchoring techniques are identified in case of difficulty with planned approach.
- Rot-resistant species are used (see *Tree species vs. rot resistance* table).
- Use slash, tree tops, and rock to infill open space in log jams.
- Flow over the log jams does not directly attack the bank and cause erosion between the structures.
- Log jams are built to the bank height or higher than the opposite bank.
- Log jams are oriented normal to the flow or slightly downstream to move flow away from bank.
- Other methods are considered that complement the log jam approach.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Log sills

Visualizing the method:
See Figure 48.

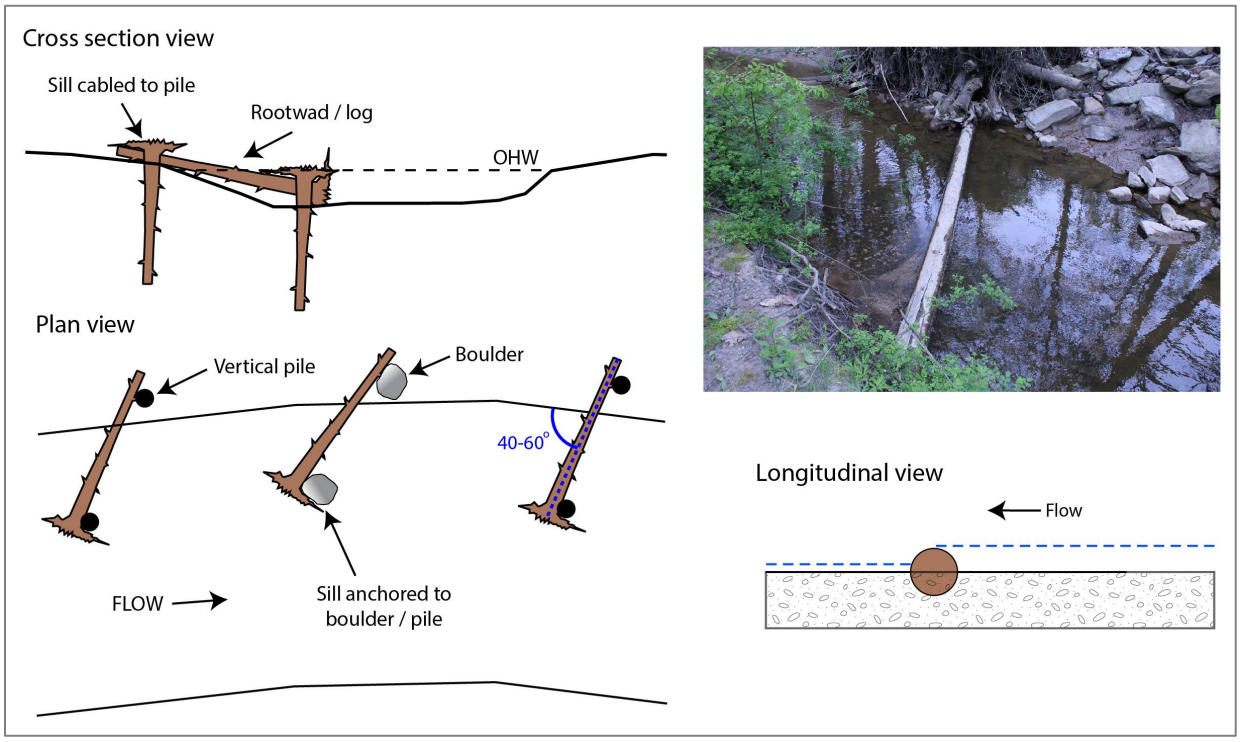


Figure 48. Schematic depicting log sill installation and field photo of a log sill on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:
Log sills (or log vanes) are a flow deflection technique consisting of a single low-profile log angled slightly upstream that redirects flow passing over the log towards the center of the channel and away from the eroding bank. Use of root wads are optional. For larger streams, multiple stacked logs (2 logs at the base and one at the top) can be used, but sills are most appropriate for smaller, lower-energy streams with low banks. The log sills are ideally anchored in place with vertical log piles: nearly all of the log length should be driven into the bed with the inverted root wad draped over the sill log to hold it in place. The logs slope downward from the bank to the channel and can be held in place by burying one end of the log in the channel bed or pinching the logs between large boulders. Several log sills built in series are needed for effective bank stabilization. Sediment deposition in between sills at the base of the stabilized bank is possible.

Applicability:
See Figure 49.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Log sills	△	△	△	◆	◆	△	●	△	●	●	△	●	●	△	●	●	△

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
△ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 49. Appropriateness of log sill technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 21. NPS

Considerations:

- Sills should protrude < ⅓ channel's width to prevent impacts to opposite bank
- Space sills 3 to 5 times the length they extend into stream to prevent erosion in between
- Sills are designed to be overtopped, so should not be higher than ⅓ bank height
- $$: Heavy machinery and large trees typically needed, but limited material needs
- Sills should be angled upstream 40–60 degrees from the bank line
- Good habitat and flow complexity created around the log sills
- Anchoring using vertical piles is best, so need to know if piles can be driven into bed
- Use native, rot-resistant species to extend functional life for decades

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Log sills protrude < ⅓ of the channel's width to prevent impacts on the opposite bank.
- The log sill spacing is appropriate for the channel size (i.e., 3 to 5 times the length the sills protrude into channel).
- Log sills are angled upstream at an appropriate angle (i.e., 40–60 degrees from the bank line).
- Alternative anchoring techniques are identified in case of difficulty with planned approach.
- Rot-resistant species are used (see *Tree species vs. rot resistance* table)
- Flow over the log sills does not directly attack the bank and cause erosion between the structures.
- Log sills are built to less than ⅓ the bank height.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Rock deflectors

Visualizing the method:
See Figure 50.

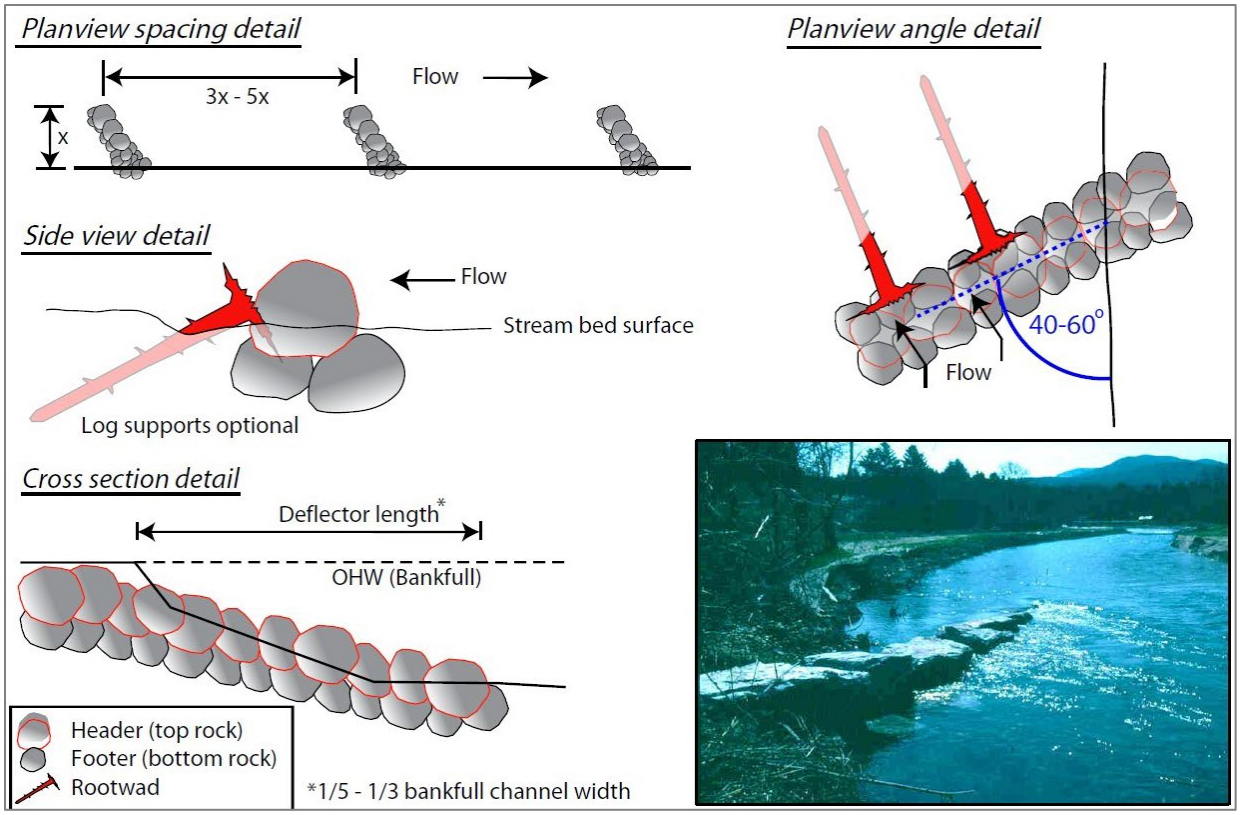


Figure 50. Schematic depicting rock deflector installation and field photo of a rock deflector on a riverbank. NPS / FIELD GEOLOGY SERVICES, LLC

Description:

Rock deflectors (i.e., barbs, spurs, and groins) are a flow deflection technique consisting of a line of boulders angled upstream to redirect flow passing over the boulders away from an eroding bank. For large rivers, the boulders at the surface should rest on footer boulders set below the river bed to prevent undermining by scour. The boulders should be sized to resist movement by the expected design forces, but root wads with the attached log buried in the channel bed can further support the boulders and double as habitat features. Deflectors typically slope down from the bank into the channel, but should not be longer than ⅓ of the channel width during the common flood to prevent impacting the opposite bank and should not be higher than ⅓ of the flow depth during the common flood to prevent outflanking the structure. Several deflectors are built in series along the entire eroding bank to prevent flow from being redirected toward the bank.

Applicability:

See Figure 51.

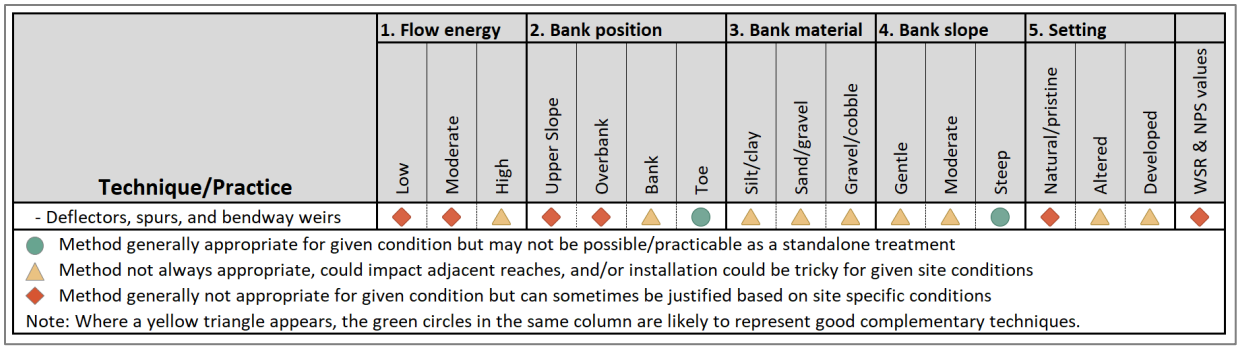


Figure 51. Appropriateness of rock deflector technique for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 22. NPS

Considerations:

- Best for use on wide channels where an unvegetated bar is present across channel
- Space deflectors 3 to 5 times the distance they protrude into channel to prevent erosion between structures
- Pools often scoured at tips of structures to create habitat but can undermine structure
- $$: Heavy machinery and large boulders are typically needed (trees are also useful)
- Deflectors should be angled upstream 40–60 degrees from the bank line
- Deflectors are designed to be overtopped, so should not be higher than ⅓ of the bank's height
- Use footer boulders and log supports in high-energy settings to prevent rock movement
- Extend structures into bank and/or protect bank at structure to prevent outflanking

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Rock deflectors protrude < ⅓ of the channel's width.
- Rock deflector spacing is appropriate for the channel size (i.e., 3 to 5 times protrusion or crest length).
- Deflectors are angled upstream at appropriate angle (i.e., 40–60 degrees from the bank line).
- Footer boulders and/or support logs are used if in high-energy environment.
- Local and sub-rounded boulders have been sourced and are of adequate size to resist the erosive force during the design flow.

- Flow over the deflectors does not directly attack the bank and cause erosion between the structures.
- Rock deflectors are built to less than ⅓ the bank height.
- Deflectors are used on the entire eroding bank and are keyed into the bank to prevent outflanking.
- Other wood-based flow deflection methods, such as engineered log jams and log sill, have been considered.
- Issues concerning recreational hazards have been addressed.

Stabilization Method Fact Sheets for WSR/NPS Managers

The method: Bendway weirs

Visualizing the method:
See Figure 52.



Figure 52. Schematic depicting installation of bendway weirs. US ARMY CORPS OF ENGINEERS

Description:
Bendway weirs are similar to rock deflectors in that they are a flow deflection technique consisting of a line of boulders angled slightly upstream to redirect flow passing over the boulders away from the eroding bank. Bendway weirs, however, have a level top elevation from the bank out to the tip of the structure, whereas rock deflectors slope downward from the bank. As a result, bendway weirs are low-profile structures that are completely submerged at high flows and may experience less severe scour at their tips compared to rock deflectors. The general rules about projection lengths (< ⅓ channel width), spacing (3 to 5 times the projection length), height (< ⅓ channel depth), orientation (40–60 degrees from the bank line), and use of footers (where severe scour expected) are all similar to rock deflectors.

Applicability:
See Figure 53.

Technique/Practice	1. Flow energy			2. Bank position				3. Bank material			4. Bank slope			5. Setting			
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/clay	Sand/gravel	Gravel/cobble	Gentle	Moderate	Steep	Natural/pristine	Altered	Developed	WSR & NPS values
- Deflectors, spurs, and bendway weirs	◆	◆	▲	◆	◆	▲	●	▲	▲	▲	▲	▲	●	◆	▲	▲	◆

● Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment
▲ Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions
◆ Method generally not appropriate for given condition but can sometimes be justified based on site specific conditions
Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Figure 53. Appropriateness of bendway weirs for use on NPS-managed rivers and WSR based on the river type, bank characteristics, and setting. Refer to the main document for more information, including an explanation of the rows and columns. Tabular data shown in this figure are presented in Appendix 6, Table 23. NPS

Considerations:

- Best for use on wide channels where an unvegetated bar is present across channel
- Space weirs 3 to 5 times the protrusion length to prevent erosion between structures
- Weirs are designed to be overtopped, so should be less than ⅓ of bank height
- $$: Heavy machinery and large boulders typically needed to construct
- Weirs should be angled upstream 40–60 degrees from the bank line
- Pools often scoured at tips of structures create habitat but can undermine structure
- Use footer boulders and log supports in high-energy settings to prevent rock movement
- Use local and sub-rounded rock to ensure more natural look

A helpful checklist for reviewing plans:

- The need for stabilization has been justified and the "do nothing/land protection" option has been ruled out.
- The method is suitable for the site (see *Approaches to Managing Bank Erosion* and *Additional Ways to Approach Management of Eroding Banks* in the main manual).
- Weirs protrude < ⅓ of channel width and spacing is appropriate (3 to 5 times protrusion length).
- Weirs are angled upstream at the appropriate angle (i.e., 40–60 degrees from the bank line).
- Bendway weirs are built to less than ⅓ the bank height.
- Footer boulders and/or support logs are used if in high-energy environment.
- Local and sub-rounded boulders have been sourced and are of adequate size to resist the erosive force during the design flow.
- Flow over the bendway weirs does not directly attack the bank and cause erosion between the structures.

- Protection is provided where the weir joins the bank to prevent outflanking, ideally with brush/logs.
- Weirs are used on entire eroding bank & are keyed into bank to further prevent outflanking.
- Other wood-based flow deflection methods, such as engineered log jams and log sill, have been considered.
- Issues concerning recreational hazards have been addressed.

Native Vegetation Planting Fact Sheet for WSR/NPS Managers

Bank stabilization projects often involve planting vegetation or using live stakes and fascines that sprout when partially inserted in the bank soil. Woody trees, shrubs, and vines are generally favored. Native species should always be used on WSR bank stabilization projects. The links below provide guidance and lists of native plants for different regions or states. Not all species listed are necessarily appropriate for streamside settings, so additional research may be needed to determine the use of certain species for bank stabilization projects.

National Resources

- USDA National Plant Database
- National Wildlife Federation native plant finder
- Flora of North America
- The Biota of North America Program

Alaska

- Directory of Alaska native plant sources

Intermontane West

- Colorado Native Plant Society
- Field Guide to the Wetlands and Riparian Plant Associations of Colorado
- Idaho Native Plant Society
- Utah Native Plant Society
- Montana Field Guides

Midwest

- Plant Iowa Native Resources
- Illinois Native Plant Society
- Kansas Native Plant Society
- Native Plant Society of Texas
- Riparian Restoration on Farms and Ranches in Texas
- Oklahoma Riparian Area Management Handbook

Southeast

- Florida Native Plant Society
- Georgia Native Plant Society
- Kentucky Native Plant Society
- Louisiana Native Plant Society
- North Carolina Native Plant Society
- South Carolina Native Plant Society
- Tennessee Native Plant Society
- Tennessee Urban Riparian Buffer Handbook

Mid-Atlantic

- Virginia Native Plant Society
- Native Riparian Plants of Virginia
- Chesapeake Bay Riparian Handbook
- Native plant list for Maryland, Virginia, and West Virginia
- Riparian Buffers for Wildlife
- Forested Riparian Buffer Planting Guide for Landowners and Developers

Southwest

- Arizona Native Plant Society
- Native Riparian Plants of Santa Clara Valley, CA
- California Riparian Forests

Northeast

- Plants of the Northeast
- Native Plant Trust
- Native Shoreland/Riparian Buffer Plantings for New Hampshire
- A Field Guide to Common Aquatic and Riparian Plants of New Hampshire
- Native Vegetation for Lakeshores, Streamsides, and Wetland Buffers

Northwest

- Washington Native Plant Society
- Streamside planting guide for western Washington

Decay Resistant Woods[1]

This information can be used to select trees to use for maximizing the lifespan of bank stabilization projects, with high-resistance species likely to have the longest-lasting impacts (Table 1). While sapwood in many species, such as hemlock, has low resistance to decay, heartwood is very rot-resistant. If high-resistance species are unavailable, larger-diameter trees with low or moderate resistance may be substituted.

Table 1. Classifying resistance to decay for wood from different tree species.

Resistance	Species
High	Bald cypress (old growth)
	Catalpa
	Cedars
	Cherry, black
	Chestnut
	Cypress, Arizona
	Junipers
	Locust, black [A]
	Mesquite
	Mulberry, red [A]
	Oak (burr, chestnut, Gambel, Oregon white, post, white)
	Osage orange [A]
	Redwood (old growth)
	Sassafras
	Walnut, black
	Yew, Pacific [A]
Moderate	Bald cypress (young growth)
	Douglas-fir
	Honey locust
	Larch, western
	Oak, swamp chestnut
	Pine, eastern white (old growth)
	Southern pine (longleaf, slash)
	Tamarack

[A] Exceptional resistance.

[1] Sources: USDA Forest Products Laboratory. 1999. Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113; and Bureau of Reclamation and U.S. Army Engineer Research and Development Center, 2016, National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure.

Table 1 (continued). Classifying resistance to decay for wood from different tree species.

Resistance	Species
Low	Alder
	Ashes
	Aspens
	Basswood
	Beech
	Birches
	Buckeye
	Butternut
	Cottonwood
	Elms
	Hackberry
	Hemlocks
	Magnolia
	Maples
	Oak (red & black species)
	Pines (other than longleaf, slash, and eastern white)
	Poplars
	Spruces
	Sweetgum
	True firs (western & eastern)
	Willows
	Yellow poplar

[A] Exceptional resistance.

Appendix 2

This appendix describes methods that can be used to evaluate the cause of bank erosion and evaluate the history of watershed disturbance.

River Resource Fact Sheets for WSR/NPS Managers

The resource: Aerial photographs

Value of aerial photographs:
Recent and historical aerial photographs are valuable in determining the amount and rate of bank erosion through time and past watershed disturbances. The past position of river channels can also be used to establish potential limits of future channel migration and bank erosion. These historic limits of migration can be used to delineate the erodible corridor based on the area over which the river has migrated through time. Aerial photos can also be useful in establishing the causes of erosion by documenting natural events (e.g., landslides) or human activities (e.g., channel straightening, land clearance) that have historically occurred near known areas of bank erosion. Aerial photographs are a primary resource for establishing why erosion is occurring, how severe that erosion has been and could become, and what potential off-site bank stabilization measures might be implemented (e.g., locating abandoned side channels to reactivate).

Visualizing the use of aerial photographs:
See Figure 54.

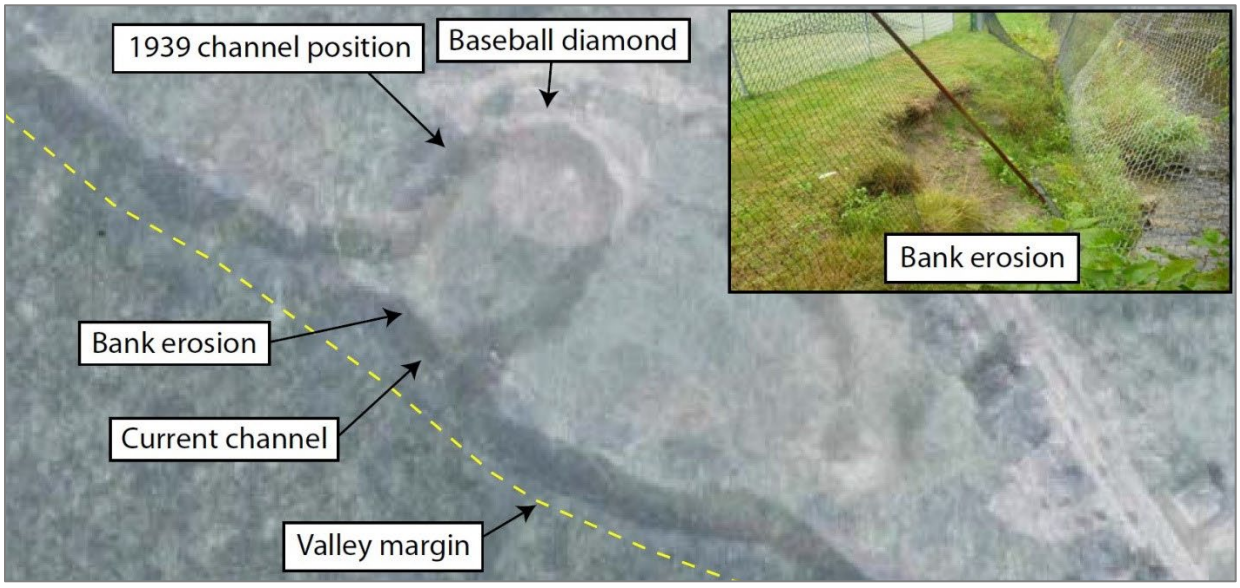


Figure 54. Overlay of recent and 1939 aerial photograph showing a meander was once present in the infield of the baseball field along a now straightened Bond Brook in Augusta, Maine. Bank erosion could be expected to continue into the infield until the former meander dimensions are reestablished, indicating aggressive bank erosion is likely. NPS / FIELD GEOLOGY SERVICES, LLC

Features to look for in aerial photographs from your watershed:
Using aerial photographs of your watershed, look for the following features (bear in mind that some features may not be present in the watershed):

- Infrastructure near the river (How close are roads and buildings?)
- Sediment deposition (i.e., sand/gravel bars) in the river (Are there nearby tributaries or landslides? Are the bars preferentially found on the inside bends of meanders?)
- Alluvial and nonalluvial reaches (Remember, sometimes each bank could be different)
- Former channel positions (i.e., oxbows and side channels) of the river (Use this to define the *river corridor,* or area within which future river migration is likely to be contained)
- Bank erosion (Use historical aerial photos to find changes in channel position through time)
- Land uses (e.g., forest, agriculture, urban) (Have any changes occurred through time?)
- Braided and meandering channel patterns (Which type predominates further downstream?)
- Human alterations of the river channel (e.g., dams, straightening, bank stabilization)

Take a driving or boat tour of the watershed and try to verify your aerial photo interpretations!

River Resource Fact Sheets for WSR/NPS Managers

The resource: Mapping channel features

Value of mapping channel features:
Mapping channel features provides a context for understanding the causes of erosion and leads to better decision-making regarding the need for and methods of bank stabilization. Typical bank erosion inventories collect details on the bank erosion itself (e.g., length, bank height, soil type) but lack context. Mapping channel features can be done with a standardized form completed for each reach of river or more comprehensively by recording the precise location of different features continuously along the river's length. The channel features mapped vary depending on the setting and project objective but may include bank stability, bank height, bank composition, bank position (e.g., inside or outside of a meander bend), radius of curvature of meander bends, sand/gravel bars, channel/bank type (i.e., alluvial vs nonalluvial), human alterations (e.g., stream crossings, riprap), forest canopy, large wood, and habitat features (e.g., pools).

The field mapping can be done inexpensively with paper copies of aerial photographs detailed enough to identify one's location while mapping on the river. However, the process is perhaps simpler and more accurate using a GPS-enabled personal device loaded with digital aerial photos and GIS software on which channel features can be recorded. Ultimately, processing the data with GIS can reveal the amount and distribution of bank erosion and provide clues to the causes of bank instability when linked to other natural and human features on the river. For example, erosion on the outside bank of a meander bend, coupled with sand bars on the inside of the meander bend, may suggest that bank erosion is caused by natural channel conditions related to meandering. In contrast, channelization by humans may be the cause of erosion where large unvegetated bars and severe bank

erosion occur together and are separated by long straight reaches with no bars and minimal erosion and/or armored (i.e., riprapped) banks.

Visualizing the mapping of channel features:
See Figure 55.

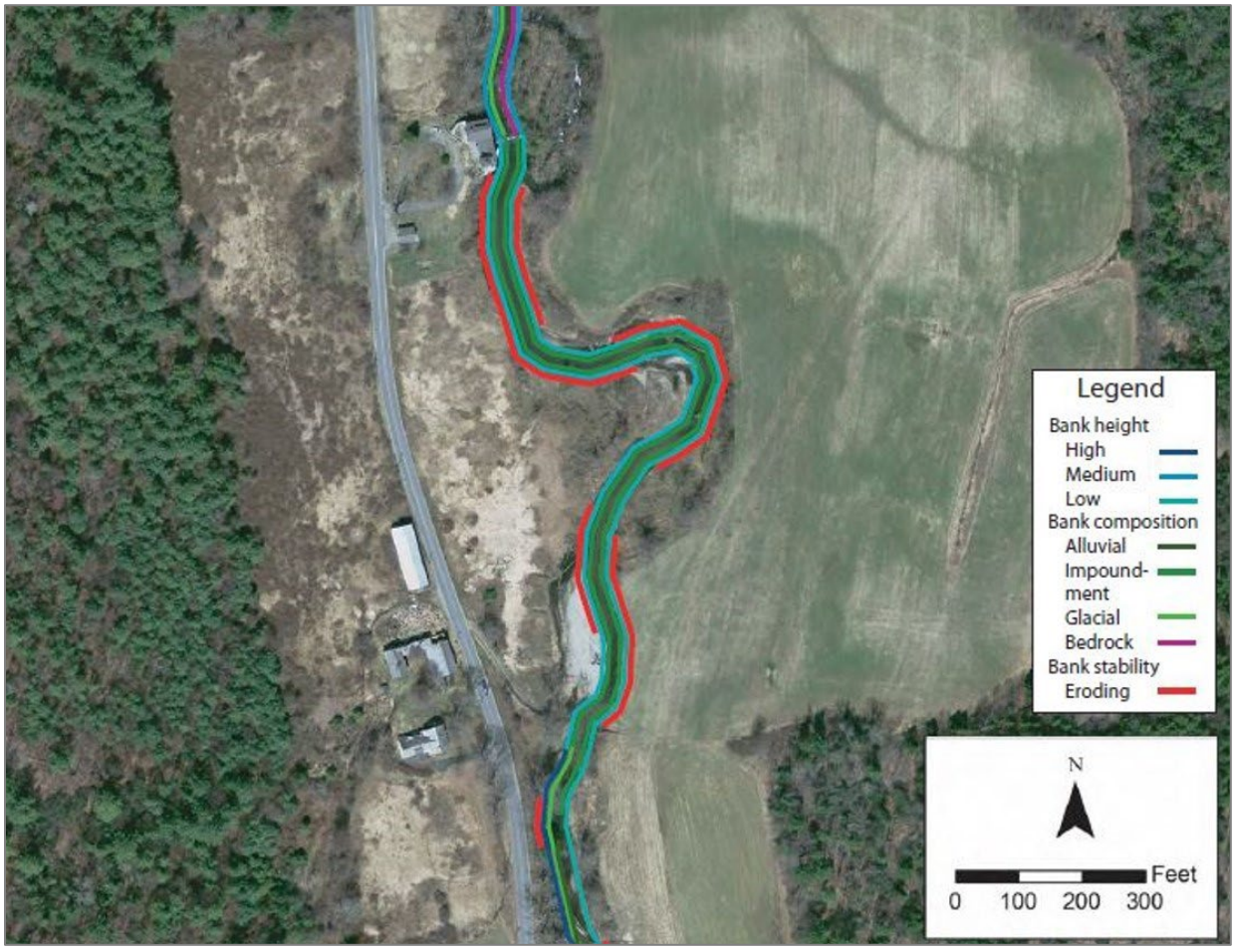


Figure 55. Channel features mapping displaying three features together along a portion of South River in Conway, Massachusetts. NPS / FIELD GEOLOGY SERVICES, LLC

Features to look for with data from channel features mapping:
Using channel features mapping data completed by yourself or available from others, try to determine the following (bear in mind that some information may not be present at your site):

- Percentage of erosion on outside bend of meanders (bank stability and position data)
- Percentage of erosion where forested buffer is absent compared to where present.
- Where can large amounts of sediment be generated (erosion & high banks occur together)?
- Erosion due to human impacts? (Erosion near crossings, straightening, armoring, etc.).
- Are habitat features threatened by erosion and sediment? (Erosion and bars near habitat)

- Is the proposed bank stabilization project at an isolated erosion site or is more erosion nearby?

Take a driving or boat tour of the mapped area and try to verify your findings!

River Resource Fact Sheets for WSR/NPS Managers

The resource: Soil and surficial geology maps

Value of soil and surficial geology maps:
Soil maps provide valuable information on the composition and erodibility of bank sediments, while surficial geology maps show the surrounding natural landscape features that might influence nearby bank erosion. Soil maps typically describe materials found in the upper one or two feet of the subsurface, but descriptions of the soil parent material sometimes indicate the composition of sediments at the base of high banks. While many soil maps are primarily focused on the agricultural productivity of the land, soil descriptions can still provide clues regarding the age of the land surface, such as young or poorly developed soils along a river indicating a modern floodplain or artificial fill. Channels where the common flood does not reach the top of a bank composed of young soils could indicate channel incision and help explain the cause of bank erosion.

Surficial geology maps show the age and distribution of land surfaces and often contain descriptions of the sediments that underlie those surfaces. Understanding the composition and stratigraphy of bank sediments is important for anticipating the character, rate, and location of bank erosion. Stratified bank sediments are more prone to erosion than banks of a uniform composition. This is particularly true where permeable sands overlay impermeable clays because water percolating through the sands will pond on the clay and then seep out of the bank in a focused area, destabilizing the bank. Field investigations of eroding bank sediments are recommended to confirm interpretations from reviewing soil and surficial geology maps.

Visualizing soil maps:
See Figure 56.

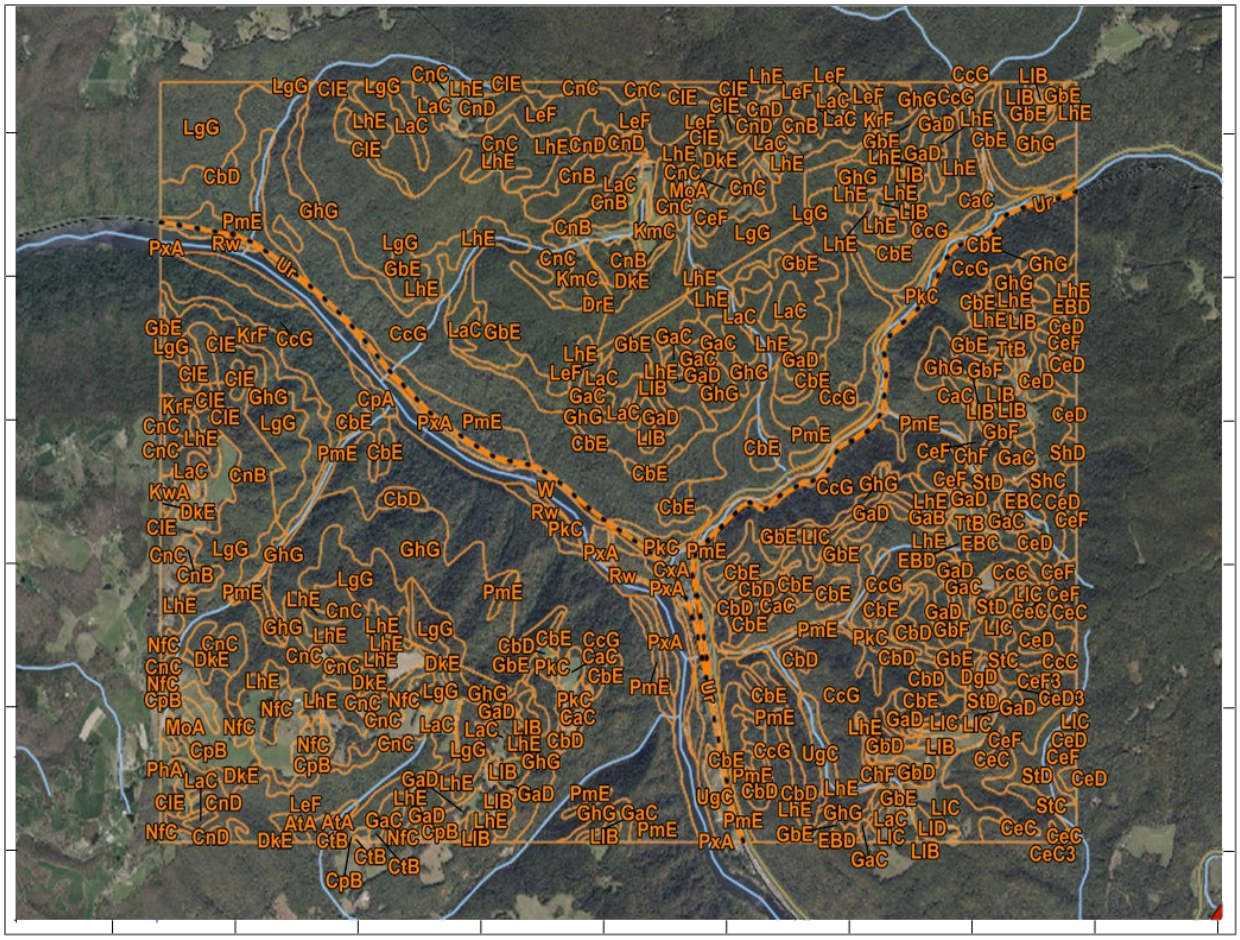


Figure 56. Soil map showing the distribution of various soil units in New River Gorge, for which detailed descriptions would be found in the accompanying soils report. NRCS

Features to look for on soil and surficial geology maps and reports from your watershed:

Using soil and surficial geology maps of your watershed, look for the following information (bear in mind that some info may not be available on the maps):

- Artificial fill on the floodplain (that may constrict flow and lead to erosion)
- Alluvial (modern floodplain soils) and nonalluvial (old soils) banks along the river
- Bank sediment is stratified (descriptions of soil units/geomorphic surfaces in reports)
- Channel incision due to human activities (High banks of fill or young soils)
- Bank erosion could occur by large rotational slumps (clay-rich soils along river)
- Uniform soil over large areas or several soil types in close proximity (with potential for different bank conditions over short distances)

Take a driving or boat tour of the area and try to verify your soil/surficial map interpretations!

River Resource Fact Sheets for WSR/NPS Managers

The resource: Topographic maps

Value of topographic maps:

Topographic maps can be used to find the slope of the river and determine whether the river is in a confined, partly-confined, or unconfined valley setting. Topographic maps can also be used to identify areas where the river is constricted by bedrock and adjacent uplands. The passage of floodwaters can be impeded by valley constrictions, causing backwatering (i.e., ponding) of flow upstream that leads to areas of deposition and bank erosion. The most unstable reaches of a river are frequently just upstream of valley constrictions, as well as at undersized bridges and culverts, although undersized crossings are hard to identify on topographic maps. Topographic maps can also be used to identify: a) high banks along the river (that might be a source of large volumes of sediment from landslides), b) grade controls such as waterfalls (that may represent the end points of influence exerted by upstream activities such as channelization), c) hillslope materials (e.g., erodible sediments will have gullies eroded into them giving rise to crenulated contour lines while hard rock with little erosion into it will be characterized by straighter contour lines), and d) alluvial channels (where perhaps only a single contour line is near the river, indicating the presence of a wide floodplain) or nonalluvial channels (where multiple closely-spaced contour lines close to and on both sides of the river indicate the river is constrained by higher slopes). Historical topographic maps for some areas extend back to the 19th century, thus providing information on channel changes (e.g., natural migration, human realignment, channel incision) over time before the earliest aerial photographs.

Visualizing the use of topographic maps:

See Figure 57.

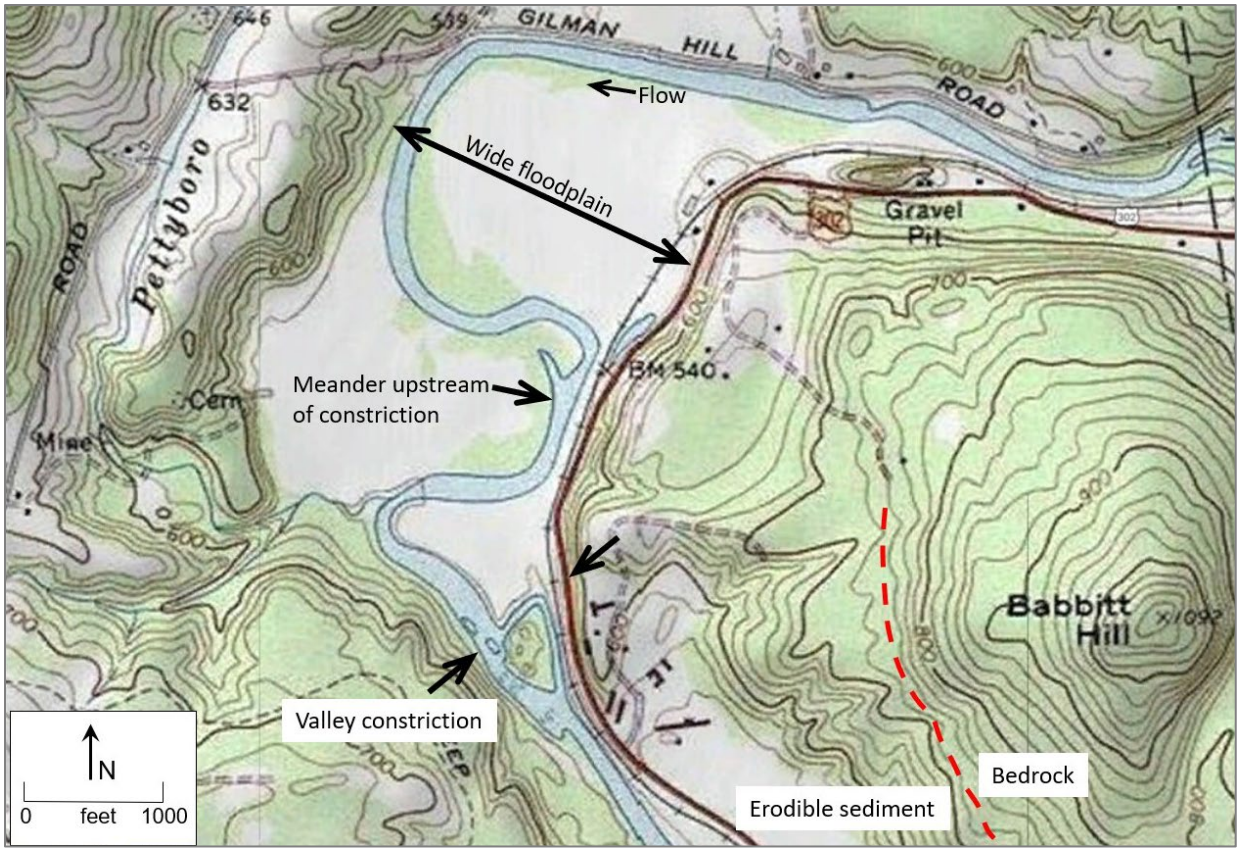


Figure 57. Topographic map of Ammonoosuc River in Bath, NH showing a valley constriction and formation of a broad, wide floodplain upstream from the construction. Note that smoothness of contour lines on hillslope provides clues to the composition. NPS / FIELD GEOLOGY SERVICES, LLC

<u>Features to look for on topographic maps from your watershed:</u>

Using topographic maps you have acquired of your watershed, look for the following features (bear in mind that some features may not be present in the watershed):

- Valley constrictions (which is where channel instabilities might be present)
- Changes in stream gradient (where waterfalls and bedrock might be present)
- Alluvial (on a wide floodplain) and nonalluvial (confined by higher banks) reaches.
- River terraces (look for flat surfaces in the valley elevated above the river & floodplain)
- High banks composed of sediment that might contribute sediment to the river (Look for crenulated contours at the base of the valley or terrace side slopes)
- Changes in the position of the channel (compare with historical topo maps)

Take a driving or boat tour of the watershed and try to verify your topo map interpretations!

River Resource Fact Sheets for WSR/NPS Managers

The resource: Topographic surveying

Value of topographic surveying:

Topographic surveys can provide valuable information on channel dimensions, slope, and other features. Although simple cross-section surveys can be completed with easily acquired materials like a tape measure and builder's level, more extensive and accurate surveys require a surveying level, electronic total station, or Real-Time Kinematic (RTK) GPS equipment. Light Detection and Ranging (LiDAR) data is becoming increasingly available throughout the U.S. to create detailed topographic maps, but usually does not provide information below the water surface. Topo surveys can create cross-sections used to determine common flood width and depth, longitudinal profiles to measure slope and riffle-pool spacing, and plan views to calculate sinuosity and create base maps. By comparing topo surveys of altered and unaltered river reaches, geomorphic assessments can reveal how the river is responding to past human alterations and thus anticipate the location and severity of future erosion.

For bank stabilization projects, surveying can establish the common flood elevation, bank height, and bank slope. This information is used to a) select treatments, b) set the elevations for transitions between treatments up the bank, c) decide whether scour protection is required below the water surface, d) compile a materials list, and e) develop a cost estimate. Cross sections repeated over time at the same location are valuable for calculating erosion rates and, when linked with stream gauge data from the same time period, can be used to establish the threshold discharge required to initiate bank erosion. The erosive forces acting on the bank during the selected design discharge can be quantified using hydraulic models that require several surveyed topographic cross-sections as input data. Hydraulic models can also predict flood magnitude, extent, and depth.

Visualizing the use of topographic surveying:

See Figure 58.

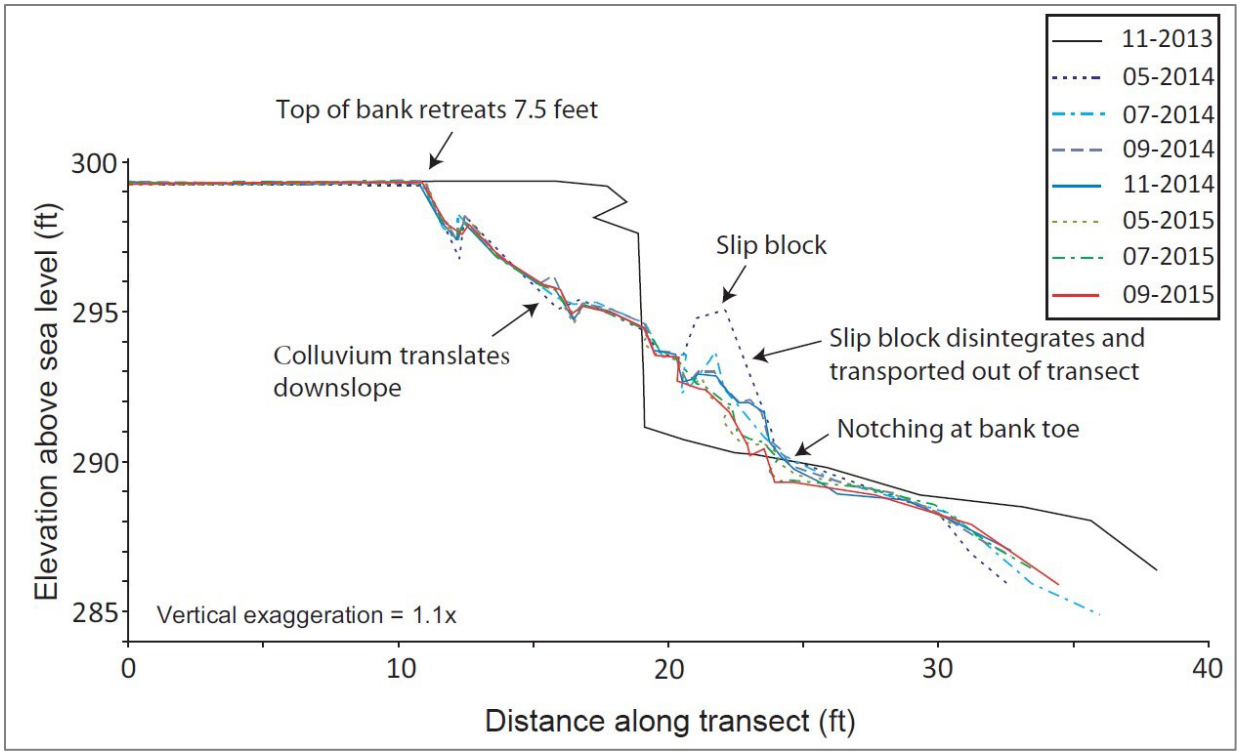


Figure 58. Bank monitoring between November 2013 and September 2015 on the Connecticut River in Charlestown, New Hampshire, shows bank retreat, slow removal of the resulting slip block, and renewed notching that will lead to further bank retreat. NPS / FIELD GEOLOGY SERVICES, LLC

Features to look for on topographic surveys from your watershed:

Using topographic survey data collected as part of a bank stabilization design or other studies, identify or measure the following features (bear in mind that some features may not be present):

- Cross-section geometry, including channel width, bank height, and channel depth (from cross sections)
- Bank slope—bank toe oversteepened suggesting imminent erosion? (from cross sections)
- Stream gradient and areas of rapid change in slope (from longitudinal profiles)
- Pool depths and spacing (from longitudinal profiles)
- Rates and style of erosion (if repeated cross-section surveys are available)
- Location of proposed transitions between treatments is appropriate (from cross sections)
- The amount of materials proposed is sufficient based on treatment length and height (from cross sections and plan view)

Take a driving or boat tour of the topographic survey sites and try to verify your observations!

Appendix 3

Annotated Bibliography of Bank Stabilization Documents

Allen, H. H., and Leech, J. R., 1997, Bioengineering for Streambank Erosion Control; Report 1, Guidelines: Technical Report EL-97-8, U.S. Army Engineer Waterways Experiment Station: Vicksburg, MS, 105 p. (Accessed December 20, 2022)

This contains conceptual design sketches for common bioengineering practices with a focus on zoning different treatments up the bank slope. Includes examples of toe treatments with wood, deformable treatments, and rock.

Bureau of Reclamation, 2015, Bank Stabilization Design Guidelines: Report No. SRH-2015-25, Albuquerque Area Office, Science and Technology Policy and Administration (Manuals and Standards), Yuma Area Office, 331 p. (Accessed December 20, 2022)

A comprehensive review of traditional (e.g., riprap), bioengineering (e.g., engineered log jams), and system (e.g., floodplain restoration) approaches to bank stabilization. The detail provided on how to develop designs is perhaps beyond the needs of watershed managers, but could be a good reference to share with an engineer who may be unfamiliar with bioengineering and system approaches to bank stabilization. Tables describe pros and cons of various techniques.

Bureau of Reclamation and U.S. Army Engineer Research and Development Center, 2016, National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure, 628 p. + Appendix. (Accessed December 20, 2022)

Resource on wood in streams including both natural occurrences and its use in stream restoration and bank stabilization. The manual's focus is not on bank stabilization, but for those considering the use of wood in bioengineering projects, the manual provides information on how to anchor wood in place, rot-resistant species to use, risks to consider, engineering analyses to undertake, and potential conflicts with recreational uses.

Colorado Water Conservation Board, 2016, Living Streambanks: A Manual of Bioengineering Treatments for Colorado Streams: 160 p. (Accessed December 20, 2022)

Briefly discusses basics of fluvial geomorphology and scouring forces that lead to bank erosion. Considerable detail on the stabilizing effect of roots on soils. Contains discussion and sketches of plant-based solutions such as staking, fascine bundles, and brush mattresses not included in other more comprehensive guides. Although specifically prepared for Colorado should be of value for those in other areas, especially in intermontane West.

Colorado Water Conservation Board, 2020. Colorado Fluvial Hazard Zone Delineation Protocol.

The State of Colorado provides an excellent diversity of resources to characterize the Fluvial Hazard Zone (FHZ). The FHZ is defined as the area a stream has occupied in recent history, may occupy, or may physically influence as it stores and transports water, sediment, and debris. This framing acknowledges that rivers are apt to abruptly change course, spread water, erode land, and deposit sediment within the corridor including the channel and nearby lands. This is a fluvial geomorphic and disturbance framework that helps river managers consider several river processes related to bank erosion.

Eubanks, E., 2004, Riparian Restoration: US Department of Agriculture, Forest Service, Technology & Development Program, 152 p. (Accessed December 20, 2022)

Not focused on bank stabilization but provides information on riparian ecosystems and their restoration. The numerous factors that must be considered in restoring full riparian ecosystem function are well-described and illustrated. Appendix G is dedicated establishing plants in arid climates.

Fischenich, J. C., 2003, Effects of riprap on riverine and riparian ecosystems: ERDC/EL TR-03-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 53 p. (Accessed December 20, 2022)

This document is essential for understanding the negative consequences of using riprap and hard armoring in bank stabilization. Although bioengineering approaches are not discussed, this publication provides a justification for their use.

Florsheim, J.L., Mount, J.F., and Chin, A., 2008, Bank erosion as a desirable trait of rivers: Bioscience, v. 58, p. 519–529. (Accessed December 20, 2022)

Important background information for anyone who undertakes or reviews planned bank stabilization projects in order to understand the potential negative consequence of bank stabilization for ecosystem and geomorphic function. Important for changing the prevalent mindset that erosion is a bad thing.

Hoag, C., and Fripp, J., 2002, Streambank Soil Bioengineering Field Guide for Low Precipitation Areas: USDA-NRCS Plant Material Center: Aberdeen, ID, 33 p. (Accessed December 20, 2022)

A much shorter guide than most others but details several techniques that can mostly be completed by hand if desired. Each technique description is organized in the same manner with simple sketches provided, so easy to digest and readily accessible to even those less familiar with the subject matter. Appendix provides some background information and some guidance on the best approach to use in different settings. The plant list provided is for drylands.

Johnson, A.W., and Stypula, J.M. (eds.), 1993, Guidelines for Bank Stabilization Projects in the Riverine Environments of King County: King County Department of Public Works, Surface Water Management Division: Seattle, WA. (Available to download in separate sections—Accessed December 20, 2022)

Thorough description of basic geology and bank erosion issues with a focus on Seattle, WA area, but has wider applicability. This is an older publication but is accessible to those less familiar with bioengineering and contains good descriptions and sketches of surface stabilization techniques (planting, fascines, brush mattresses) and how to construct them, but contains limited information on structural approaches such as engineered log jams that have become more widely used since publication. An updated version may be in development.

National Wild and Scenic River Segments (Feature Layer).

This polyline feature class depicts the classification of each Wild and Scenic River segment designated by Congress and the Secretary of the Interior for the United States and Puerto Rico. This layer was created by a multi-agency effort including the US Forest Service, National Park Service, Bureau of Land Management and the Fish and Wildlife Service.

Natural Resources Conservation Service, 1998, The Practical Streambank Bioengineering Guide: User's Guide for Natural Streambank Stabilization Techniques in the Arid and Semi-Arid Great Basin and Intermountain West: USDA Natural Resources Conservation Service, Plant Materials Center: Aberdeen, Idaho, 150 p. (Accessed December 20, 2022)

Guide focuses on arid and semi-arid regions of the western United States. Simple box diagrams illustrating basic bioengineering techniques are a bit dated but the excellent table listing tree and plant species to use for bioengineering projects is timeless and valuable for a region that is not usually a focus of more recent publications.

Sholtes, J.S., Ubing, C., Randle, T.J., Fripp, J., Cenderelli, D., and Baird, D.C., 2018, Managing infrastructure in the stream environment: Journal of the American Water Resources Association, v. 54, p. 1172–1184. (Accessed December 20, 2022)

Journal article detailing steps that can be taken to reduce conflicts between riverine systems and the built environment, both for existing infrastructure and future landuse planning.

USGS Water Data for the Nation.

These pages provide access to water-resources data collected at approximately 1.9 million sites in all 50 States, the District of Columbia, Puerto Rico, the Virgin Islands, Guam, American Samoa and the Commonwealth of the Northern Mariana Islands.

Washington State Department of Transportation, 2019, Hydraulics Manual M 23-03.06: Environmental and Engineering Programs Hydraulics Office, 235 p. (Accessed December 20, 2022)

The manual provides a great deal of information on the hydrologic and hydraulic methods to be used for various engineering aspects related to road construction, including culvert sizing and bank stabilization. While many aspects of the manual are specific to Washington State, those in other areas

of the country should still find considerable information of value and relevance. Much of the bank stabilization aspects are drawn from Washington's 2002 Integrated Streambank Protection Guidelines (see above). The manual has a very useful section on the use of Large Woody Material including the best tree species to use and how to calculate the stability of log structures in the stream. While the technical detail may not be accessible to the typical river manager, the manual is a suitable resource for an engineer who needs some guidance and background on utilizing wood in a bank stabilization design.

Appendix 4

Best Practices and Required Measures to Use in Section 7 Determinations Related to Bank Stabilization Projects

Appendix 4 pertains to Section 7 project reviews that are required on WSR. However, the information in this appendix may be useful for planning stabilization projects on NPS rivers as well. Section 7 is a key provision of the Wild and Scenic Rivers Act directing federal agencies to protect designated rivers and congressionally authorized study rivers from the harmful effects of water resources projects. It requires evaluation of federally-assisted water resources projects and a determination by the river-administering agency. During the Section 7 coordination process, river managers often encourage proponents to incorporate various best practices, as appropriate, for bank stabilization projects. River managers may also require implementation of specific avoidance and minimization measures and actions for the duration of the project. The ability of the river manager to render a favorable Section 7 determination often rests on the fulfillment of these required avoidance and minimization measures. River managers should *select and tailor* from the menus below the specific required measures (conditions) necessary for the project to avoid, eliminate, reduce, or minimize impacts on WSR values. Selection should be commensurate with the scope and complexity of the project.

1. Project Coordination

Best Practices

- Project coordination is a critical component of a successful Section 7 determination process. Early engagement with project proponents is particularly helpful.
- Interparty coordination should occur early, and then as necessary throughout the process, to ensure WSRA compliance and avoid last-minute changes or project delays.
- It may be necessary to recruit a representative partner to participate at meetings that the NPS is not able to attend. This could be a fellow DOI Agency with mutual interest in the project (e.g., USFWS) or a state river manager (e.g., DNR) in the case of a 2(a)(ii) river.
- For complex projects or those that could have significant impacts, consider establishing an interdisciplinary team or request technical assistance from the appropriate regional and/or national support office (e.g., engineering specialists; hydrologists and fluvial geomorphologists in the NPS Water Resources Division; geologists in the NPS Geologic Resources Division).
- Conducting interparty on-site planning meetings, project reviews, and pre-construction meetings with project planners and equipment operators is strongly recommended to ensure all parties involved have a complete understanding of the project requirements, definitions and conditions.
- It is often helpful to request that the project proponent provide copies of engineering plans and specifications following the completion of each major design phase (e.g., 30%, 60%, 90% of project completion). While a preliminary Section 7 determination may be made based

on conceptual plans, the final Section 7 evaluation and determination should be based on a review of engineering plans that are nearly (at least 60%, but preferably 90%) complete.

- NPS should perform project plan reviews, comment on preliminary project construction plans, and monitor on-site construction activities. Site visits and on-site construction reviews can identify maintenance needs and chronic problems that may be occurring.
- Section 7 determinations should recite required measures and additional provisions that must be met to satisfy the determination, including language that requires the completed project to be consistent with the project plans evaluated on a specific date and identified with a specific title so that there is no ambiguity or misunderstanding. Whenever possible, it is also helpful to seek inclusion of similar language in engineering plans (e.g., in the general or construction notes sections) or supplemental specifications, as well as in any other required permits such as USACE Section 404 permits. Such inclusion increases the likelihood that the contractor submits a bid and performs construction with full understanding of and compliance with the required measures.
- The Section 7 determination should provide the project proponent with a formal approval or denial of the project. An example of the language to include is as follows:
    - The National Park Service has determined on behalf of the Secretary of the Interior, pursuant to Section 7 of the Wild and Scenic Rivers Act, that the proposed project would not have a direct and adverse effect on the free-flowing condition, water quality or outstandingly remarkable values of the [*insert WSR name*], provided that the project is constructed consistent with the [insert project proponent name] plans entitled [insert project title] dated [insert date], and that the avoidance and minimization measures and actions cited below are fully and properly fulfilled, for the duration of the project [insert list of avoidance and minimization measures and conditions].
- The NPS should require and conduct a site walk-thru with the contractor upon "substantial completion" of construction activities. Other federal and state permitting agencies should be invited to participate. A completion report should be prepared in a timely manner. Any practice failures should be identified and remedied at this time. Often there is a performance warranty period of 2 to 5 years after the completion of the project.

<u>Required Measures</u>

- The project proponent must provide NPS with an approved and complete project plan set, including any relevant special provisions or supplemental specifications, along with all design and engineering plans.
- NPS must be notified of any proposed changes to the project package originally submitted for evaluation, such as the plan set, special provisions, construction methods, or schedule for instream work. Any such changes require consultation with NPS before the work proceeds and may require additional Section 7 review and approval. The project proponent may be required to undo or change any construction that was not part of the approved package.

- NPS must be notified and invited to all pre- and post-construction agency coordination meetings, including final site inspections.
- Remedial actions must be implemented in a timely manner.
- A pre-construction meeting with equipment operators must be held prior to project commencement to discuss project requirements.
- NPS must be promptly notified of accidents and/or failures of project features intended to protect the free-flowing condition, water quality, or Outstandingly Remarkable Values (ORV) during construction activities.
- The contractor must invite the NPS to conduct a site walk-thru upon "substantial completion" of construction activities, prior to demobilization.
- The project proponent must submit a post-construction report to the NPS within 90 days of project completion. The report should include a set of before and after pictures along with a written summary of the project, any complications or challenges, and any solutions or deviations to plans.

2. Preconstruction Studies

Best Practices

- It is often necessary and appropriate for NPS to request additional information in the form of pre-construction studies (e.g., for a bank stabilization project this might include geotechnical borings, habitat surveys, soils analysis, geomorphic assessments, topographic surveys, and hydraulic modeling). It is the responsibility of the project proponent to provide the necessary data for the evaluating agency to make an informed determination.
- Baseline inventories of Outstandingly Remarkable Values (ORVs) and aquatic and terrestrial resources will better inform the project planning and design process.
- For areas supporting federal or state-listed species, informal and/or formal consultation with the USFWS and/or state resource management agencies may be necessary.

Required Measures

- Appropriate biological inventories of aquatic (e.g., fish, mussels) and terrestrial resources may be required prior to project startup. Avoidance measures must be developed in consultation with the NPS. Cultural resources inventories may also be required in order to comply with Section 106 of the National Historic Preservation Act.
- Relocation of mussel species is required where in-stream work cannot be avoided within reaches of known mussel populations. USFWS and/or state resource agencies must be consulted to ensure any established mussel relocation protocols are followed.
- Appropriate geotechnical, hydraulic, visual resource, auditory, or other project-specific resource studies may be required prior to project start. Avoidance measures must be developed in consultation with the NPS.

- Appropriate hydrologic/hydraulic information (e.g., scour depth analysis) may be required to accompany or be included in all design and engineering plans for the project.

3. Notification to River Users

Best Practices

- Bank stabilization work can pose a safety hazard to river users. It is important to warn the recreating public of any temporary hazards associated with the construction activity and provide instruction on how to safely avoid an unsafe situation.

Required Measures

- Boating (canoe/kayak or other) shall be safely maintained throughout the duration of the project either within the existing river channel or through a temporary portage trail. The route must be approved by NPS and other agencies as necessary.
- Construction during peak recreational season must be avoided unless otherwise authorized in writing by the NPS and/or other recreation agency. Avoidance measures must be developed in consultation with the NPS.
- Press releases shall be issued to local media prior to project implementation and signs must be provided to recreational river users and canoe livery operators advising them of closures and/or portage routes and their effective dates.
- A portage route must be maintained around the site during construction and removed (and the site restored to its original condition) upon project completion. Any exceptions to this condition must be approved by the NPS and/or other recreation agencies prior to project implementation or as may be necessary during project construction. Signage announcing the temporary portage will be removed at project completion.

4. Erosion Control

Best Practices

- Water quality management is delegated to state and local resource agencies. Erosion control often falls to local zoning, conservation commissions, and NPDES permits or Section 401 water quality certifications under the Clean Water Act. By coordinating with the appropriate agencies and including specific conditions about sediment erosion control, effective protections for riverine health can be implemented.

Required Measures

- Water quality shall be maintained by implementing appropriate erosion prevention and sediment control practices from the [*insert name of state water pollution control agency*]'s [*insert title of erosion and sediment pollution control guidance document*] [*insert date of publication (month year)].*
- No hay bales shall be used for erosion and sediment controls; certified weed-free, chemical-free straw bales are acceptable.

- Woven and mechanically-bound biodegradable erosion control matting shall be used to stabilize all slopes steeper than 3H:1V. No plastic netting or welded joint poly-based matting shall be used.
- Native seed mixes and plant species shall be used to reestablish vegetation. No borrow, loam, or fill material shall contain invasive species.
- All mulch fibers and tackifiers used for hydroseeding shall be biodegradable and non-toxic. Fiber must be at least 50 percent wood fiber. Paper mulches and polymeric emulsion blends are not permitted. Seed mixes shall be native and not contain invasive species. No hydraulic mulch or tackifiers shall be placed below the ordinary highwater mark.
- An erosion and sediment control plan must be developed for the site and remain on site for the duration of the project. Particular attention shall be given to any drainage ways, ditches and streams that could convey sediment-laden water directly to the [*insert stream name].* Appropriately designed rock or log check dams and other erosion controls shall be utilized in ditches and drainage ways.
- A phased construction schedule must be utilized to minimize open areas and reduce the potential for erosion. Temporary vegetative cover must be used to stabilize areas that are not subject to active construction. Any exceptions to these conditions must be authorized by the NPS in writing or otherwise made part of this determination.
- Appropriate sediment/stormwater controls must be installed prior to grading or other land-disturbing activities.
- Properly installed (framed and entrenched) silt fence shall be properly installed around the work site perimeter and stormwater inlets.
- All erosion control devices shall be inspected daily and properly maintained until final site stabilization is achieved. Accumulated sediment shall be cleaned out of erosion control devices, and worn-out or deteriorated materials must be replaced on a regular basis.
- All sediment and erosion controls shall be removed upon stabilization of the project area with vegetation.
- All denuded areas, including ditches, culverts, and river/stream banks, shall be permanently seeded [*insert recommended or approved native seed type/source*] and mulched (or covered with biodegradable fiber mat material) immediately upon completion of earthwork or temporarily seeded and mulched (or covered with fiber mat material) within seven days if the area is to remain idle for more than thirty days.
- Where working directly in the water, turbidity shall be monitored at downstream locations during construction and work immediately shut down if turbidity exceeds a predetermined level set after consultation with appropriate federal, state, and local authorities.

5. Construction Equipment/Staging Areas/Work Site

Best Practices

- A majority of impacts to the river that are attributed to construction activities can be avoided by maintaining a tidy site. Proactive site management minimizes the potential for unintended consequences. Standard best practices include scheduling to avoid sensitive periods, biological monitoring, erosion and sediment control, and revegetation with native riparian species.

Required Measures

- Litter and construction debris shall be contained daily. Construction and/or worker-generated debris/garbage must be contained on site in properly covered containers; daily clean up must be performed to prevent materials from entering the river.
- Excavators working in the stream channel must use approved nontoxic, biodegradable hydraulic fluid. “Fish-friendly” hydraulic fluid is defined as a synthetic thermally stable biodegradable hydraulic oil (ISO 32/46). Contractor shall certify in writing that equipment is bled and filled with “fish-friendly” lubricants and hydraulic fluids when stipulated prior to beginning operations.
- All construction equipment must be inspected daily for hydraulic and fuel leaks and repaired as necessary. When not in use, idle equipment, petrochemicals and toxic/hazardous materials shall be locked and may not be stored in the 100-year floodplain or near any drainage ways, ditches, or streams; discharge of petroleum products, cement washings, or other construction materials into the river is not permitted.
- All fueling operations, lubricating, hydraulic topping off, fuel tank purging, and equipment maintenance/repairs shall be performed at an upland site outside of the 100-year floodplain. These activities shall take place on an approved pad with spill control/collection devices in place, and the operator trained in their use. The use of canola oil or other biodegradable fuels and fluids is recommended when working in sensitive riverine environments.
- Appropriate oil spill kits shall be maintained on site and readily accessible at all times during construction and each operator trained in their use.
- No wastewater shall be discharged into the river.
- Prior to moving construction equipment into the project area, the contractor must take reasonable measures to ensure that each piece of equipment is free of soil, seeds, vegetative matter, or other debris that may contain seeds of non-native invasive species (consider including aquatic if equipment will be used in-stream).
- All tools, equipment, barricades, signs, surplus materials, and rubbish from the project work limits shall be removed upon project completion. All construction debris and litter must be completely removed off-site and disposed of properly upon completion of the project.

- All debris, excess fill material and material excavated shall be disposed of at an approved upland location (above 100-year flood elevations). Disposal in wetlands, floodplains or within 1000 feet of the [*insert river name*] is prohibited.
- Hazmat booms encircling the work area shall be deployed to ensure any accidental fuel leaks are captured before moving downstream.

6. Vegetative Plantings/Tree Removal/Tree Replacement

Best Practices

- Trees that are preserved in the project work area will help to maintain bank stability, terrestrial habitat, and riverine aesthetics.

Required Measures

- Avoid unnecessary tree removal within the project work area.
- A vegetation plan shall be in place to protect existing vegetation/trees from damage by construction equipment (e.g., provide temporary barriers to protect existing trees, plants, root zone).
- Disturbances of the riparian zone must be limited to the indicated access points; prior to the operation of heavy equipment (dozers, cranes, trucks), orange construction fencing must be erected to delineate the dripline of remaining trees to avoid compaction of tree roots.
- The fastening of ropes, cables, or fencing to trees is prohibited.
- To ensure bank stability, trees removed within fifteen feet of the top of the riverbank shall be cut flush to the ground; stumps and roots shall be left in place; indiscriminate bulldozing of riparian trees is prohibited.
- All trees removed from the riparian corridor shall be replaced with a native tree of like species. Replace each mature tree removed (12-inch or greater diameter at breast height [DBH]) with [*insert specifications, e.g., replant 3:1 ratio depending on expected survival rate and with trees that are a minimum 3-inches DBH*]. Plant only local, native trees/shrubs/grasses, naturally occurring within the [*insert river name*] riparian zone such as [*insert plant species list and/or to be determined in coordination with appropriate staff*].
- A qualified individual (arborists, foresters, or trained staff with similar experience) shall plant replacement trees at the appropriate time of year and in a random fashion to avoid a plantation effect. Cultivate and monitor planted tree seedlings/saplings for two years to ensure success; water plantings as necessary. Promptly replace planted stock showing signs of mortality.
- Stakes and guide wires shall be properly removed and disposed of once seedlings are established.

7. Archeological/Cultural Resources

Best Practices

- Engage the Section 106 process at the earliest stages (i.e., planning), ensuring identification of historic properties (including archaeological sites) has been completed within the area of potential project effects. See "Appendix L: Section 7 Coordination—National Historic Preservation Act" in Reference Manual 46: Wild and Scenic Rivers (dated June 12, 2019) for more information about coordinating the Section 106 and Section 7 review processes.
- Incorporate efforts to protect known/unknown archeological resources in the area into the planning process. Coordinate with the State Office of Historic Preservation (SHPO) and/or Tribal Historic Preservation Office (THPO).

Required Measures

- Should previously unknown archeological materials be discovered during land clearing or other construction activities, consult and coordinate with the SHPO/THPO before work resumes. Properly document results of consultation and additional practices that need to be implemented.

8. Bank Protection (General)

Best Practices

- The use of native boulders and cobbles, along with native plantings and bioengineering, will best achieve the desired natural appearance and functioning riverbank after construction is complete.

Required Measures

- Minimize the use and visibility of rock channel protection (RCP) and use only the minimum amount necessary to protect structures. Integrated plantings, soil, and native seed may be used to further reduce the profile of visible rock.
- If required, rock used for riprap shall be native, sub-angular to sub-rounded stone from a local quarry. Stone riprap shall not exceed an elevation greater than one (1) foot higher than the Ordinary High Water Mark (OHWM). See Endnote 6 on the Section 7 flowchart for OHWM mark definition.
- Rock slope protection shall be used only where a shear stress analysis has determined that stone fill is necessary. All stone fill *below* OHWM shall be choked with native stream bed materials. Stone fill shall be sub-rounded to sub-angular particles and installed in multiple lifts if necessary to ensure voids are fully choked. All stone fill *above* OHWM (only where necessary) shall be choked and covered with clean topsoil and seeded with native plant species or combined with bio-engineering techniques such that the banks, when fully restored, have an appearance and function similar to the natural streambank. No stone fill shall be placed above the 10-year flood elevation; fabric encapsulated soil lifts are acceptable.

- Riparian areas must be restored to pre-disturbance conditions immediately after construction activities are completed.
- Disturbed/exposed banks, staging and project access areas must be properly stabilized (seeded, mulched, or otherwise) with native vegetation to prevent erosion and establishment of invasive plant species. A non-persistent cover crop of annual rye or equivalent temporary seeding may be used to ensure a more rapid establishment of cover while native perennial plantings grow.
- Bio-engineering methods must be used or, where deemed necessary by the [*insert river managing agency/contact*], clean fractured rock riprap of adequate size for the specific bank stabilization.
- The use of demolition debris for slope armoring is not allowed.
- Native seed mixes and plant species shall be used to reestablish vegetation. Plantings shall include a mix of woody shrub and tree species. No borrow, loam, or fill material shall contain invasive species.
- Approximately [*four to six*] months following planting, the plantings shall be inspected. Any dead, dying, or damaged plantings shall be replaced. Any replacement plantings shall be completed within 30 calendar days after of inspection or as directed by the site engineer. The cycle shall continue until a 90% survival rate has been achieved to the satisfaction of the site engineer, the National Park Service, and the US Army Corps of Engineers.
- Downstream flows shall always be maintained, with water from dewatering operations filtered to remove excessive sediments and discharged in a manner that prevents a release of turbid water into downstream areas. Entrapped fish or mussels shall be collected and relocated to the stream channel in a timely manner that promotes their safe recovery.
- Where disturbed during construction of the bank stabilization project, the stream bed shall be reconstructed using a well-graded mix of materials that simulate natural substrate and stream conditions and allow for aquatic organism passage.

Required Measures and Material Specifications for Specific Bank Stabilization Methods

1. Planting Vegetation

- Plant material from commercial sources or from NRCS Plant Material Centers (PMC) shall be harvested just before shipment to the site or harvested no earlier than two months before planting and stored in refrigerated storage at 40 to 50 degrees Fahrenheit.
- When shipped, plants shall be transported in enclosed or covered trucks and scheduled to arrive on site within 24 hours.
- Transported plants shall be bundled and packed to prevent damage to the bark, limbs, or root systems.
- All rooted plants shall be treated with a root gel to prevent drying.

- The plant materials should be planted the day they arrive on site or, if they cannot be planted the day they arrive, shall be stored on site under a wet tarp to protect them from wind, direct sunlight, drying or other damage.
- Cuttings or unrooted stock that is not planted within two days after arrival on the site shall be discarded unless refrigerated at 40 to 50 degrees Fahrenheit.
- Rooted stock that is not planted within five days after arrival on site shall be discarded, unless stock is refrigerated at 40 to 50 degrees Fahrenheit. Discarded materials shall be replaced from commercial sources at the contractor's expense.
- All planting of woody vegetation shall be accomplished during the dormant season (please check your local area as to the exact timing of the dormant season).
- Installation of plant materials should begin concurrently with the earth moving operations and should be completed no later than 10 days after a cut or fill slope has been prepared. When the planting is delayed beyond 10 days, the slope shall be protected from erosion by mulching with straw mulch at a rate of 2 tons per acre or the installation of biodegradable erosion control blankets.
- Place plants in holes made with a planting bar or shovel on the natural or reshaped bank surface. The holes shall be of sufficient size to permit placing the plant without bending the root. Place the plants in the hole to the same depth as they were originally growing before harvest.
- Plant rooted cuttings or seedlings on approximately 5-foot centers in rows along the contour of the slope. Install rows of plants approximately 5 feet center to center measured parallel to the slope and stagger the plants from row to row.
- All rooted plantings shall be dipped in a root gel just prior to planting.
- Holes made with a shovel shall be filled with excavated soil and pressed firmly around the roots up to the ground surface. Holes made with a planting bar may be closed with the planting bar firming the soil at the bottom of the hole first and then firming the soil at the top. All spaces within one foot of the planting shall be filled with soil and compacted.
- All plant materials damaged during installation or determined to be unsuitable by the technician shall be removed and replaced at the contractor's expense.

2. Fascine Bundles

- Pruning cuts or cuts for live unrooted cuttings shall be smooth and shall not damage the remaining bark of the plant.
- Fascine bundles shall be prepared from live, native shrubby material of species which will root, such as Salix species (willow), Cornus species (dogwood), Alnus species (alder), etc.
- Fascine bundles may vary in length, depending on materials available and size of workforce.
- Diameter of branches used in fabrication shall not be more than 1½ inches in diameter.

- Stems shall be placed in the same direction and overlapped to create a shingled effect.
- When compressed firmly and tied, each bundle shall be approximately 8 inches in diameter.
- Fascines shall be tied on not more than 24-inch centers with a minimum of two wraps of natural biodegradable bailing twine by a non-slipping knot.
- Plant materials for fascines shall be harvested from existing stands of living woody vegetation.
- Harvesting shall be done by hand or with small equipment so there will be minimal disturbance to the harvesting site.
- The materials shall be cut with loppers, pruners, or other devices that will provide a smooth cut without damage to the bark of the cutting or the remaining plant.
- Cuts shall be made at an angle of approximately 45 degrees to ensure that the plants will regenerate rapidly and in a healthy manner.
- Live cuttings shall be bundled together securely at the collection site with branches and limbs kept intact and transported to the work site in enclosed or covered trucks.
- Live cuttings shall be sprayed with water and covered with a wet tarp during storage and transport.
- Live cuttings should be installed within 24 hours of harvest.
- Live cuttings that cannot be installed within 24 hours shall be stored at temperatures of 40 to 50 degrees Fahrenheit to ensure protection.
- Storage shall provide protection from the wind, direct sunlight, and drying by covering live cuttings with a wet tarp.
- Cuttings must be refrigerated if the air temperature is above 50 degrees F.
- The harvesting site shall be left in a condition that will enhance the regeneration of the plants.
- Remnant materials from the harvesting operation shall be chipped or left in piles for wildlife cover.

3. Live Stakes

- Pruning cuts or cuts for live unrooted cuttings shall be smooth and shall not damage the remaining bark of the plant.
- Live stakes shall be living, woody plant cuttings with side branches removed and the bark intact.
- Live stakes must be taken from a native species that roots easily from cuttings, such as willow.
- Live stakes shall be prepared from ½ to 2-inch diameter stock and cut into lengths of 2 to 3 feet.

- The basal or butt ends of stakes shall be cleanly cut at an angle to facilitate easy insertion into the soil.
- The tops of stakes should be cut square or blunt.
- Plant materials for live stakes shall be harvested from existing stands of living woody vegetation.
- Harvesting shall be done by hand or with small equipment so there will be minimal disturbance to the harvesting site.
- Live stakes shall be cut with loppers, pruners or other devices that will provide a smooth cut without damage to the bark of the cutting or the remaining plant.
- Cuts shall be made at an angle of approximately 45 degrees to ensure that the plants will regenerate rapidly and in a healthy manner.
- Live cuttings shall be bundled together securely at the collection site and transported to the work site in enclosed or covered trucks.
- Live cuttings shall be sprayed with water and covered with a wet tarp during storage and transport.
- Live cuttings should be installed within 24 hours of harvest.
- Live cuttings that cannot be installed within 24 hours shall be placed in storage, at 40 to 50 degrees F for protection.
- Storage shall provide protection from the wind, direct sunlight, and drying by covering cuttings with a wet tarp.
- Cuttings must be refrigerated if the air temperature is above 50 degrees F.
- The harvesting site shall be left in a condition that will enhance regeneration of the plants.

4. Brush Mattresses

- Live brush shall consist of the whole above ground portion of willow, red osier dogwood, alder, or other hardwood species which root easily from cuttings.
- Plants shall be 5 to 6 feet tall.
- When there is a shortage of willow and other rooting species, up to 50 percent of the brush may be non-rooting species.
- When non-rooting species are used, they shall be mixed randomly with the rooting species.
- Brush will have good contact with the underlying soil to ensure regeneration.
- Brush mattresses will be anchored with live stakes with a minimum length of 24 inches using a native species with a 2 to 4-inch diameter.
- Dead stout stake may be used if live stakes are unavailable as long as any timber used is untreated and is sound material.

- Brush mattresses can be further secured using two wraps of natural biodegradable bailing twine by a non-slipping knot.
- The use of wire for securing the brush mattresses shall not be allowed.
- Plant materials for brush mattresses shall be harvested from existing stands of living woody vegetation.
- Harvesting shall be done by hand or with small equipment so there will be minimal disturbance to the harvesting site.
- The materials shall be cut with chainsaws, brush axes, loppers, pruners or other devices that will provide a smooth cut without damage to the bark of the cutting or the remaining plant.
- Cuts shall be made at an angle of approximately 45 degrees, 8 to 10 inches above the ground, to ensure that the plants will regenerate rapidly and in a healthy manner.
- Live cuttings shall be bundled together securely at the collection site with branches and limbs kept intact and transported to the work site in enclosed or covered trucks.
- Live cuttings shall be sprayed with water and covered with a wet tarp during storage and transport.
- Live cuttings should be installed within 24 hours of harvest.
- Live cuttings that cannot be installed within 24 hours shall be placed in storage, at 40 to 50 degrees Fahrenheit for protection.
- Storage shall provide protection from the wind, direct sunlight, and drying by covering cutting with a wet tarp.
- Cuttings must be refrigerated if the air temperature is above 50 degrees Fahrenheit.
- The harvesting site shall be left in a condition that will enhance the regeneration of the plants.
- Remnant materials from the harvesting operation shall be chipped or left in piles for wildlife cover.

5. Log Jams, Log Crib Walls, and Root Wad Revetments

- Trees to be used in the construction of the wood buttress shall consist of a mix of species including at least 50 percent of the most rot-resistant species that are readily available (see Rot resistance chart).
- For channels greater than 10 feet wide, tree diameters at breast height (DBH) shall range from 12 to 18 inches with less than 25 percent 12 to 14 inches DBH.
- For channels less than 10 feet wide, tree diameters as small as 6 inches DBH are acceptable as long as 50 percent are greater than 8 inches DBH.
- Root wads and logs shall be derived from live trees harvested no sooner than the dormant season prior to construction.

- Root wads shall not be trimmed in order to provide functional refugia habitat for fish and other aquatic organisms.
- Live conifers and other trees shall be felled or pulled/pushed over in upland areas and shall not be taken from floodplain or riparian areas.
- Wood shall be anchored by driving vertical piles with at least half the log length driven below the surface and then interweaving other logs between the piles and/or infilling the structures with gravel, cobble, or boulder ballast if such rock is found naturally along the river.
- Where wood is to be anchored into the bank, the width of excavated trenches shall not exceed two times the log width and trench length should not be more than one foot longer than the length of log to be buried.
- No cable or rebar shall be used to anchor wood structures.
- Smaller limbs and branches created from the harvesting of trees shall be brought to the site and used as fill within the log structures.

6. Rock Revetments

- Rock revetments shall use only the minimum amount of rock necessary to protect structures or outstandingly remarkable values. Integrated plantings, soil, and native seed may be used to further reduce the profile of visible rock.
- Rock used in the revetments shall be of native, sub-rounded stone from a local quarry and will need to be at least 20 percent larger in size than that calculated for angular stone.
- Rock revetments shall not exceed an elevation greater than one foot higher than the Ordinary High Water Mark (OHWM).
- Rock revetments shall be choked with native streambed materials.
- The rock shall be sound and dense, free from cracks, seams, and other defects that would tend to increase deterioration from weathering, freezing, and thawing, or other natural causes.
- Rock shall be from a local native source and have a minimum specific gravity of 2.5.
- The subgrade surface on which the rock riprap, filter, bedding, or geotextile is to be placed shall be cut or filled and graded to the lines and grades shown on the drawings.
- Fill, when required, shall consist of approved material and be free of seeds of nonnative species.
- The rock shall be delivered and placed in a manner that ensures the revetment is reasonably homogeneous, with the larger rocks uniformly distributed and firmly in contact with one another and the smaller rocks filling the voids between the larger rocks.
- Filter, bedding, or geotextile materials underlaying the rock, where needed, shall make use of local natural materials free of nonnative seeds or be biodegradable, and the surface of such material shall be finished reasonably smooth and free of mounds, dips, or windrows.

7. Rock Deflectors

- Rock deflectors shall be built low enough to be completely overtopped during channel-forming (i.e., bankfull) flow events.
- The tops of rock deflectors shall have spaces between the exposed rock to improve flow complexity but shall be touching at their base to improve stability.
- Rock deflectors shall not be used in sand-bed rivers.
- Rock deflectors should be constructed during low flow conditions to minimize instream disturbances.
- The rock shall be sound and dense, free from cracks, seams, and other defects that would tend to increase deterioration from weathering, freezing, and thawing, or other natural causes.
- The rock fragments shall be rounded to sub-rounded in shape.
- The smallest dimension of an individual rock shall not be less than one-third the greatest dimension of the rock.
- Rock shall be from a local native source and have a minimum specific gravity of 2.5.

Sources

The above best practices, required measures, and materials specifications are based, in part, on the following sources:

Bureau of Reclamation and U.S. Army Engineer Research and Development Center, 2016, National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure, 628 p. + Appendix. (Accessed December 20, 2022)

National Park Service, 2021, Reference Manual 46: Wild and Scenic Rivers, 193 p. (see Appendix I) (Accessed December 20, 2022)

Natural Resources Conservation Service, 2009, Construction specification 61—Rock riprap: National Standard Construction Specifications, Part 642, National Engineering Handbook, 210-VI-NEH, 4 p. (Accessed December 20, 2022)

Natural Resources Conservation Service, 2006, Vermont construction specification 56—soil bioengineering plantings: NRCS-VT FOTG Section IV, 5 p. (Accessed December 20, 2022)

Natural Resources Conservation Service, 2001, Design of rock weirs: Technical Notes—Engineering No. 13, 8 p. (Accessed December 20, 2022)

Appendix 5

US Army Corps of Engineers

Resources for Navigating the Regulatory and Permitting Processes

- US Army Corps of Engineers District Website (Accessed 7/10/2023)—Interactive Map of USACE Districts across the USA, with links to each District and its accompanying resources. In most Districts web pages, you can select the "Missions" menu at top, and the relevant resources will be nested under the "Regulatory" subtopic.
- Example Regulatory & Permitting Resources for select USACE Districts
    - New England District Website (Accessed 12/20/2022)—New England District with links to state general permits for the six New England states as well as other useful links including information on invasive species and naturalized river restoration and bank stabilization in New England
    - Baltimore District Website (Accessed 12/20/2022)—Baltimore District with links to state general permits in the Mid-Atlantic (including Washington, D.C.) and other links explaining permit process
    - Rock Island District Website (Accessed 12/20/2022)—Rock Island (Illinois) District with links to midwestern state general permits and other useful links
    - Portland District Website (Accessed 12/20/2022)—Portland (Oregon) District providing links to permits and other useful information

Appendix 6

Tables 2 to 23 present the data from figures found earlier in the report. Table captions include hyperlinks to the corresponding figures.

Table 2. Data from Figure 7. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Preserve erodible corridor	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Watershed management	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Relocate infrastructure	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Reactivate side channels	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle
Offsite Measure: Floodplain reconnection	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle
Offsite Measure: Dam Removals	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle

Table 2 (continued). Data from Figure 7. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Offsite Measure: Reform meanders	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle
Offsite Measure: Increase channel/ floodplain roughness	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Vegetative Surface Treatment: Planting native trees, shrubs, etc.	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle
Vegetative Surface Treatment: Live stakes	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Vegetative Surface Treatment: Fascine bundles	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle

Table 2 (continued). Data from Figure 7. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Brush mattresses	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Vegetative Surface Treatment: Hydroseeding and mulching	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle
Wood Surface Treatment: Log crib walls	Yellow Triangle	Yellow Triangle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Red Diamond
Wood Surface Treatment: Tree revetments	Green Circle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle
Wood Surface Treatment: Root revetments	Green Circle	Green Circle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle
Deformable Surface Treatment: Bank reshaping	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle

Table 2 (continued). Data from Figure 7. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Fabric-encapsulated soil lifts	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle
Deformable Surface Treatment: Rock/sand bags	Yellow Triangle	Green Circle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Yellow Triangle
Deformable Surface Treatment: Coir logs	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle
Deformable Surface Treatment: Erosion control blankets	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Red Diamond	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle
Hard Armoring Surface Treatment: Rock revetments (riprap)	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond

Table 2 (continued). Data from Figure 7. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Hard Armoring Surface Treatment: Retaining walls (e.g., gravity block)	Red Diamond	Red Diamond	Red Diamond	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond
Flow detection techniques (wood): Engineered marginal log jams	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle
Flow detection techniques (wood): Log sills	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle
Flow detection technique (rock and concrete): Deflectors, spurs, and bendway weirs	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Green Circle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond

Table 3. Data from Figure 13. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Preserve erodible corridor	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle

Table 4. Data from Figure 15. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Offsite Measure: Watershed management	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Relocate infrastructure	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Reactivate side channels	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle
Offsite Measure: Floodplain reconnection	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle

Table 4 (continued). Data from Figure 15. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on site-specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Offsite Measure: Dam Removals	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle
Offsite Measure: Reform meanders	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle
Offsite Measure: Increase channel/ floodplain roughness	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle

Table 5. Data from Figure 17. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Planting native trees, shrubs, etc.	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle

Table 6. Data from Figure 19. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Live stakes	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle

Table 7. Data from Figure 21. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Fascine bundles	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle

Table 8. Data from Figure 23. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Brush mattresses	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle

Table 9. Data from Figure 25. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Vegetative Surface Treatment: Hydroseeding and mulching	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle

Table 10. Data from Figure 27. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Wood Surface Treatment: Log crib walls	Yellow Triangle	Yellow Triangle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Red Diamond

Table 11. Data from Figure 29. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Wood Surface Treatment: Tree revetments	Green Circle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle

Table 12. Data from Figure 31. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Wood Surface Treatment: Root revetments	Green Circle	Green Circle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle

Table 13. Data from Figure 33. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Bank reshaping	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle

Table 14. Data from Figure 35. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Fabric-encapsulated soil lifts	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle

Table 15. Data from Figure 37. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Rock/sand bags	Yellow Triangle	Green Circle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Yellow Triangle

Table 16. Data from Figure 39. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Coir logs	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle

Table 17. Data from Figure 41. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Deformable Surface Treatment: Erosion control blankets	Green Circle	Yellow Triangle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Red Diamond	Green Circle	Green Circle	Red Diamond	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Green Circle

Table 18. Data from Figure 43. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Hard Armoring Surface Treatment: Rock revetments (riprap)	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond

Table 19. Data from Figure 45. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Hard Armoring Surface Treatment: Retaining walls (e.g., gravity block)	Red Diamond	Red Diamond	Red Diamond	Red Diamond	Red Diamond	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond

Table 20. Data from Figure 47. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Flow detection techniques (wood): Engineered marginal log jams	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Green Circle	Green Circle	Green Circle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle

Table 21. Data from Figure 49. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Flow detection techniques (wood): Log sills	Yellow Triangle	Yellow Triangle	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle	Green Circle	Green Circle	Yellow Triangle

Table 22. Data from Figure 51. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Flow detection technique (rock and concrete): Deflectors, spurs, and bendway weirs	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Green Circle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond

Table 23. Data from Figure 53. Green Circle: Method generally appropriate for given condition but may not be possible/practicable as a standalone treatment; Yellow Triangle: Method not always appropriate, could impact adjacent reaches, and/or installation could be tricky for given site conditions; Red Diamond: Method generally not appropriate for given condition but can sometimes be justified based on-site specific conditions. Note: Where a yellow triangle appears, the green circles in the same column are likely to represent good complementary techniques.

Technique/ Practice	1. Flow Energy			2. Bank Position				3. Bank Material			4. Bank Slope			5. Setting			WSR & NPS Values
	Low	Moderate	High	Upper Slope	Overbank	Bank	Toe	Silt/ Clay	Sand/ Gravel	Gravel/ Coble	Gentle	Moderate	Steep	Natural/ Pristine	Altered	Developed	
Flow detection technique (rock and concrete): Deflectors, spurs, and bendway weirs	Red Diamond	Red Diamond	Yellow Triangle	Red Diamond	Red Diamond	Yellow Triangle	Green Circle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Yellow Triangle	Green Circle	Red Diamond	Yellow Triangle	Yellow Triangle	Red Diamond

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