RECLAMATION

Managing Water in the West

Managing Infrastructure in the Stream Environment

Advisory Committee on Water Information
Subcommittee on Sedimentation
Environment and Infrastructure Working Group

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2017

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and Tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Cover Images: Left – Former site of Glines Canyon Dam on Elwha River, Washington (Copyright by John Gussman, 2017). Right Top – Culvert blocking sediment transport downstream (Daniel Cenderelli). Right Bottom – Bridge span than accommodates flood flows and sediment transport (Daniel Cenderelli).

Managing Infrastructure in the Stream Environment

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Prepared by:

Joel S Sholtes[1], Caroline Ubing[1], Timothy J Randle[1], Jon Fripp[2], Daniel Cenderelli[3], and Drew C Baird[1]

1: Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group, Denver, Colorado
2: Natural Resources Conservation Service, National Design, Construction, and Soil Mechanics Center, Fort Worth, Texas
3: U.S. Forest Service, National Stream and Aquatic Ecology Center, Fort Collins, Colorado

Peer Reviewers:

Jennifer Bountry, Bureau of Reclamation
Brian Cluer, National Marine Fisheries Service
Mathias Collins, National Oceanic and Atmospheric Administration
Katherine Dahm, Bureau of Reclamation
April Fitzner, Bureau of Reclamation
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Martin Teal, WEST Consultants, Inc.
Steven Yochum, U.S. Forest Service

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Executive Summary

Riverine infrastructure provides essential services that are necessary for the operation and development of our Nation and its economy. It has increased our agricultural productivity, re-routed floodwaters away from populated areas, connected cities, formed vital components of our transportation network, and provided a variety of other services ranging from water delivery to erosion prevention. In this guidance document, 11 types of riverine infrastructure and management issues are discussed:

1. floodplain encroachment (general development in the floodplain)
2. large wood management
3. pipelines
4. levees and dikes
5. streambank protection
6. stormwater infrastructure
7. channelized rivers
8. grade control structures
9. transportation infrastructure
10. dams and reservoirs
11. surface water diversions

When much of this infrastructure was built, fluvial processes and stream ecology were not well understood. Therefore, in many cases, existing riverine infrastructure is in conflict with the stream environment or at risk from it. This incompatible infrastructure has led to the degradation of stream ecosystems by contributing to habitat loss, water quality deterioration, and physically unstable streams. High maintenance costs are often required to keep such infrastructure viable. Furthermore, failure of riverine infrastructure resulting from river hazards is a threat to public safety. Through infrastructure planning and design we can replace and repair aging and damaged infrastructure, or decommission it. We have the opportunity to consider approaches that promote healthier stream ecosystems, while reducing exposure to hazards and associated maintenance costs. A more holistic and systems-based approach can be applied to planning, designing, and maintaining infrastructure that is better adapted for the stream environment.

This guidance document lays the foundation for infrastructure designers and managers—from the local to the Federal level—to understand how to build, maintain, or decommission infrastructure in a manner that is both resilient to riverine hazards (i.e.. floods and channel migration), aligned with local stream ecosystem needs, rehabilitation, and preservation objectives. It introduces fundamental geomorphic and ecosystem concepts and provides recommended steps for replacing, repairing, or building new infrastructure. The four stages of riverine infrastructure planning and design discussed are:

1. identifying project goals, scope, and constraints
2. evaluating hazards and values of the project
3. formulating alternatives
4. evaluating alternatives for the decision-making process and implementation of the project

This document discusses common problems as well as stream-compatible design approaches for the 11 different infrastructure and stream management topics. A discussion of each type of riverine infrastructure follows a description of how infrastructure and the stream corridor interact, and how infrastructure can be better built and managed within the stream corridor. This document concludes with a discussion on managing infrastructure under hydrologic uncertainty. For example, infrastructure designers may consider safety factors, robust design, or adaptive management approaches to addressing uncertainty. A list of design manuals and guidance documents in the appendix support the recommended management and design options.

Acronyms

CWA	Clean Water Act
DOI	Department of the Interior
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FISRWG	Federal Interagency Stream Restoration Working Group
ft^3/s	cubic feet per second
m	meter(s)
NEPA	National Environmental Protection Act
Reclamation	Bureau of Reclamation
U.S.	United States

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I. Introduction

Federal, State, and local agencies, along with private citizens, have worked to construct and manage a vast network of infrastructure within stream corridors. The infrastructure and associated construction includes channel and floodplain modifications (i.e., hydrologic changes, channelization, urbanization, removal of large wood, and agriculture), streamside infrastructure (roads, pipelines, levees, streambank protection, and storm-water infrastructure), and stream crossing infrastructure (bridges and culverts, pipelines, grade control structures, dams, reservoirs, and surface water diversion structures). Riverine infrastructure provides vital services which often come at the cost of impacts to the stream ecosystem and pose a potential liability in terms of public safety and maintenance costs.

Much of the infrastructure in the United States (U.S.) was built in the early and middle 20th century and is nearing the end of its design life, defined as the time period infrastructure is designed to function assuming routine maintenance [1]. During this construction boom in the last century, impacts to the stream environment from infrastructure, as well as impacts of dynamic streams on infrastructure, were not often considered. Furthermore, infrastructure designers did not have the benefit of the current level of scientific understanding of stream processes and hazards. Some of those existing infrastructure or land use practices are not compatible with the stream environment and are not sustainable without high maintenance costs and ongoing degradation to stream ecosystems. Given these issues, the U.S. is currently at a juncture where infrastructure management and ecosystem rehabilitation may find mutual solutions [2]. As new infrastructure is built, old infrastructure is replaced or decommissioned, or when infrastructure is damaged by catastrophic events, we have an opportunity to both increase infrastructure resiliency and rehabilitate stream ecosystems.

A more holistic and systems-based approach is suggested for planning, designing, and maintaining infrastructure that is compatible with and sustainable in the stream and riparian environment. Such an approach to riverine infrastructure management can result in more resilient infrastructure and more valuable and robust ecological systems. An example is setting back infrastructure away from the migration paths of stream channels (stream-side roadways), or avoiding the migration path of meanders (stream crossings). When there is no alternative to avoid constructing infrastructure close to stream channels and within floodplains, features can be designed to minimize the impact to the environment and be resilient to flood hazards (see Box 1). Stream corridor habitat that provides shade, cover, and hydraulic complexity can help mitigate the impacts caused by infrastructure. Rehabilitation and preservation of stream corridors offer approaches to offset environmental impacts. When infrastructure must be

Box 1.—Big Thompson River – U.S. Highway 34 Improvements

After a devastating flood in 2013, the Colorado Department of Transportation repaired and re-built a canyon-bound highway. Many portions of the highway were washed out, especially where the road ran along the outside of river bends (right). The highway was elevated above and moved away from one such high hazard area as part of the post-flood reconstruction. Other resilient designs include setbacks from the river, vegetated floodplain benches, and integration of vegetation into embankments. Though costly, these improvements reduce the risk of future damage and the economic costs of losing a major transportation corridor from the next flood.

replaced or repaired, compatibility with the stream environment should be considered along stream and floodplain rehabilitation options to mitigate impacts. Managing riverine infrastructure within the context of master plans that account for watershed-scale processes and environmental concerns can result in proactive and more resilient, rather than reactive, infrastructure programs.

This guidance document lays the foundation for managers to understand how to build, maintain, or decommission infrastructure in a manner that is both resilient to riverine hazards (i.e., floods and channel migration), and aligned with local stream ecosystem needs and rehabilitation objectives. This document also introduces fundamental physical and ecological stream processes and discusses how infrastructure and development within stream corridors impact these processes. From a flood hazard perspective, it reviews how dynamic streams and riverine infrastructure can conflict. This document outlines systems-based approaches to addressing the impacts of channel and floodplain modifications, streamside infrastructure, and stream crossing infrastructure that may be influenced by construction, maintenance, or decommissioning needs. The important topic of improving habitat and the environment adjacent to current infrastructure is also described.

A decision tool is provided to inform best practices for approaching riverine infrastructure management under different scenarios in Section III-A. Case studies in Section III-B highlight how ongoing management of riverine infrastructure can align with stream ecosystem rehabilitation objectives. This document does not provide prescriptive measures or specific design guidance. Guidance documents specific to riverine infrastructure are referenced in the appendix. With this guidance document, managers and designers are provided with the knowledge and tools to begin the conversation about how to best manage riverine infrastructure, increase their resiliency, and improve stream ecosystems.

II. Fundamental Principles of Physical and Ecological Stream Processes

Stream corridors are dynamic and complex systems that support aquatic (within the stream), riparian (adjacent to the stream), and terrestrial (land-based) ecosystems. In this document we use the term stream to refer to all linear waterways from creeks and washes to rivers and estuaries. Stream corridor refers to the stream and adjacent lands within a stream valley and active floodplain. Streams continually change at rates related to their position within a watershed (defined as an area of land that drains all streams and rainfall out of a common outlet [3]) or the erodibility of their bed and banks. Confined canyon streams change little and very slowly, while unconfined alluvial valley streams may change more rapidly. Alluvial refers to streams whose bed and banks are composed of mobile material and are able to modify their channel via erosion and deposition of sediment. Streams with substantial bedrock or large boulders present in their boundaries are not often alluvial. In floodplain settings, change may be incremental, for example, due to gradual bank erosion and meander migration. Episodic events like floods or landslides can cause rapid changes such as channel widening, realignment, and even the creation of new flow paths within the floodplain, potentially impacting riverine infrastructure. Disturbance can be beneficial from an ecological perspective. Floods create and maintain complex and diverse aquatic, riverine, and terrestrial habitats, sustaining crucial ecosystems.

Connectivity, defined as the movement of flow, materials, and organisms, is a fundamental concept in contemporary stream research and management [4]. For example, longitudinal connectivity refers to pathways of flow, sediment, organic matter, and organisms through stream corridors. Lateral connectivity is the exchange of this material between the stream channel(s) and adjacent floodplains and riparian areas. The following is a brief introduction of fundamental stream processes as they relate to riverine infrastructure, ranging from the physical to the biological. Riverine hazards associated with floods are also introduced.

A. Dynamic Equilibrium and Channel Response

Stream form is defined as the shape of the channel cross section (width, depth, bank slopes), planform (channel pattern as viewed from above), and longitudinal profile (channel slope and slope breaks). Stream form in alluvial channels results from the interaction of the channel shaping factors of flow and channel slope with resisting factors such bed material size, incoming sediment load, the presence and density of riparian vegetation, and geologic controls such as valley shape and the presence of bedrock. This balance is conceptualized in Lane's balance (figure 1), [5, 6].

Channel equilibrium occurs when the driving and resisting forces in streams are balanced (figure 1). The prevailing flow regime and slope provide enough mechanical energy to transport the quantity and size of the incoming sediment load with a given channel roughness, influenced by vegetation, bed sediment grain size, and channel geometry. However, if one of the parameters change, the balance will tip and one or more of the other three variables must adjust to establish a new equilibrium. For example, if slope were to increase due to channel straightening and flow discharge remained constant, sediment load and/or sediment size must proportionally increase to maintain the new slope, or the slope must reduce via channel incision, or erosion of the channel bed.

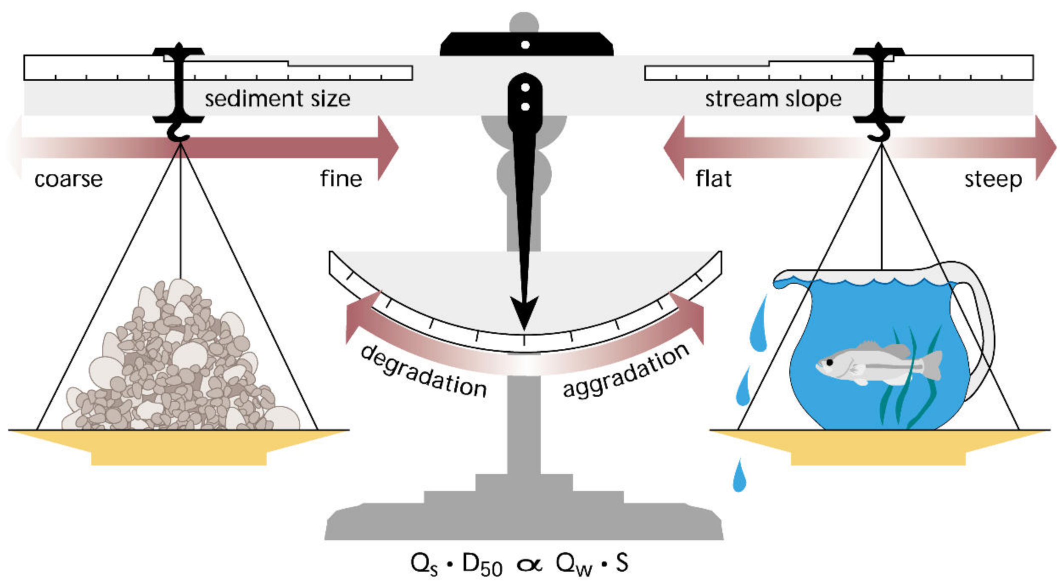

Figure 1.—Lane's channel stability balance describes how changes in sediment load, size, stream slope, discharge, and channel roughness determine whether a channel will aggrade or incise [7].

Typically, a channel will incise to lower its bed elevation and reduce its slope, setting off a feedback process where incision migrates upstream. Given long time periods and few boundary constraints, the straightened channel may evolve to increase its sinuosity and achieve a milder slope, one in balance with its new resisting and driving forces. This concept can be applied to understand how streams have responded to existing infrastructure, how they might respond to new and upgraded infrastructure designs, and how infrastructure can be planned to protect stream ecosystems.

Streams are not static features, but are rather in an active state and capable of transporting, storing, and remobilizing sediment, wood, and nutrients. The prevailing flow regime and sediment supply are the dominant controls influencing channel form and geometry. Alluvial streams may temporarily widen where vegetation is sparse or deepen where vegetation is dense in response to flooding. Their meander bends typically migrate downstream and across the valley bottom. Over a relatively short time period (years to decades), streams may adjust their width and channel position via lateral migration. Over longer time periods (decades to centuries), these streams are in dynamic equilibrium. Dynamically-stable streams maintain average values of width and sinuosity, but can be expected to migrate and occupy various regions within the active floodplain.

Dynamically-stable, single-thread alluvial streams that have perennial flow regimes tend to form a distinct break between channel and floodplain. The "bankfull discharge" in these streams (defined as the discharge that just fills the channel before spilling onto the floodplain) has an average annual chance of exceedance of 67 percent (1.5-year recurrence interval, figure 2, top, Stage IV, [8]). However, this annual probability can vary greatly depending on flow regime variability (linked with climate), land use, riparian and bank vegetation density, sediment supply, and local geology [9]. Effects from land use change, such as urbanization, can result in enlarged channels in which the bankfull discharge and channel geometry no longer represent stable conditions. In sand bed rivers, consideration of flow regime and sediment supply better informs estimation of bankfull discharge [10]. Although not applicable to all streams, the concept of bankfull discharge and identifying channel dimensions at this discharge are useful for managing streams and designing riverine infrastructure such as road crossings.

Channel evolution models expand upon the continuity principle associated with Lane's balance by describing the evolution of stream systems attempting to reach equilibrium in response to a disturbance (figure 2). As originally formulated by Schumm et al. [11], the conceptual model has six stages that are driven by feedback of physical processes such as sediment transport, bank stability, and sediment accumulation. Bank and riparian vegetation processes are additions made by Simon and Hupp [12]. Stage I of the model depicts a supposed pre-disturbance channel. A disturbance such as channelization or urbanization (and concomitant hydromodification) initiates the response cycle, which progresses until a new dynamic equilibrium is achieved. Hydromodification refers to changes in the rainfall-runoff relationships typically resulting from land use change such as urbanization [13]). The duration of each stage is dependent on the system and circumstances. The entire sequence can occur within an affected reach over 10 to 1,000 years [14]. Progressive stages of channel evolution may be observed moving downstream in a watershed with headwater streams experiencing Stages II through IV, and mainstem streams experiencing Stages V and VI, depending on how long the watershed has had to adjust to a disturbance.

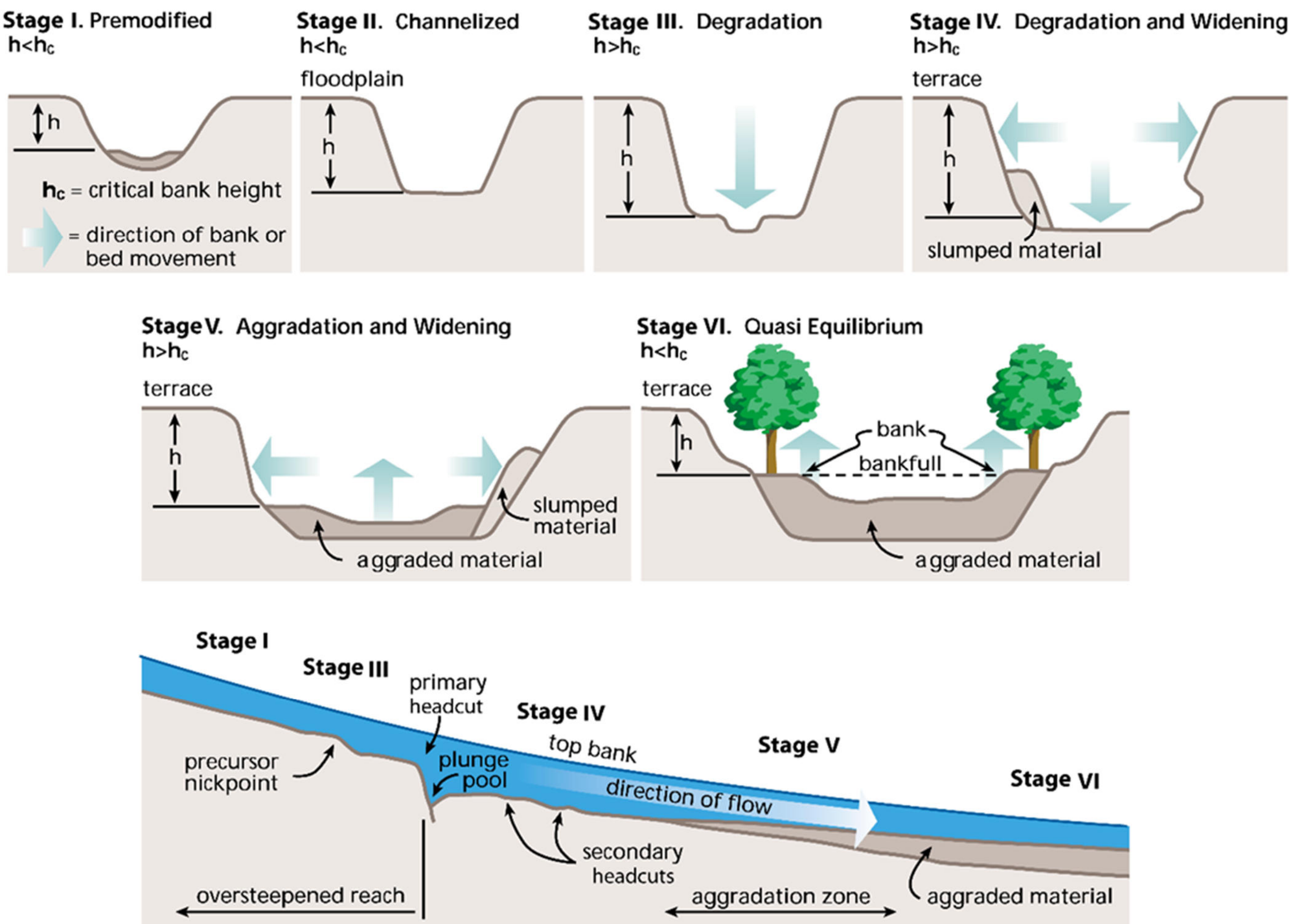

Figure 2.—Channel evolution model for incised channel response after a disturbance ([7], adapted from [11]).

B. Channel Planform

Channel planform is the shape of the channel as viewed from above. Understanding channel planform, along with the physical processes and the frequency of movement associated with a particular planform, is critical to the success of an infrastructure project built in the stream environment. Stream planforms exist on a continuum, generally divided into three categories for single-thread (one channel) streams: straight, meandering, and braided (see figure 3) [15, 16]. Single-channel, meandering streams are currently the most prevalent channel planform [17]. Multi-threaded channels with stabilizing vegetation are also a common planform, especially in less disturbed stream systems [18]. Many sinuous, single-thread streams were formerly multi-threaded prior to European settlement. Subsequent land use change that accelerated sedimentation of valley bottoms or lead to channel incision, as well as direct channelization, all have contributed to simplifying stream planform (i.e., conversion from multi- to single-thread). As sediment supply and grain size increase, and as bank resistance to erosion decreases (typically as bank vegetation density diminishes), stream planform tends to shift from sinuous or multi-threaded to braided and the level of stream dynamism—and potential hazard to riverine infrastructure—increases. Non-alluvial streams typically do not change their planform over engineering time scales (decades) as bedrock controls erode at geologic times scales (centuries to millennia).

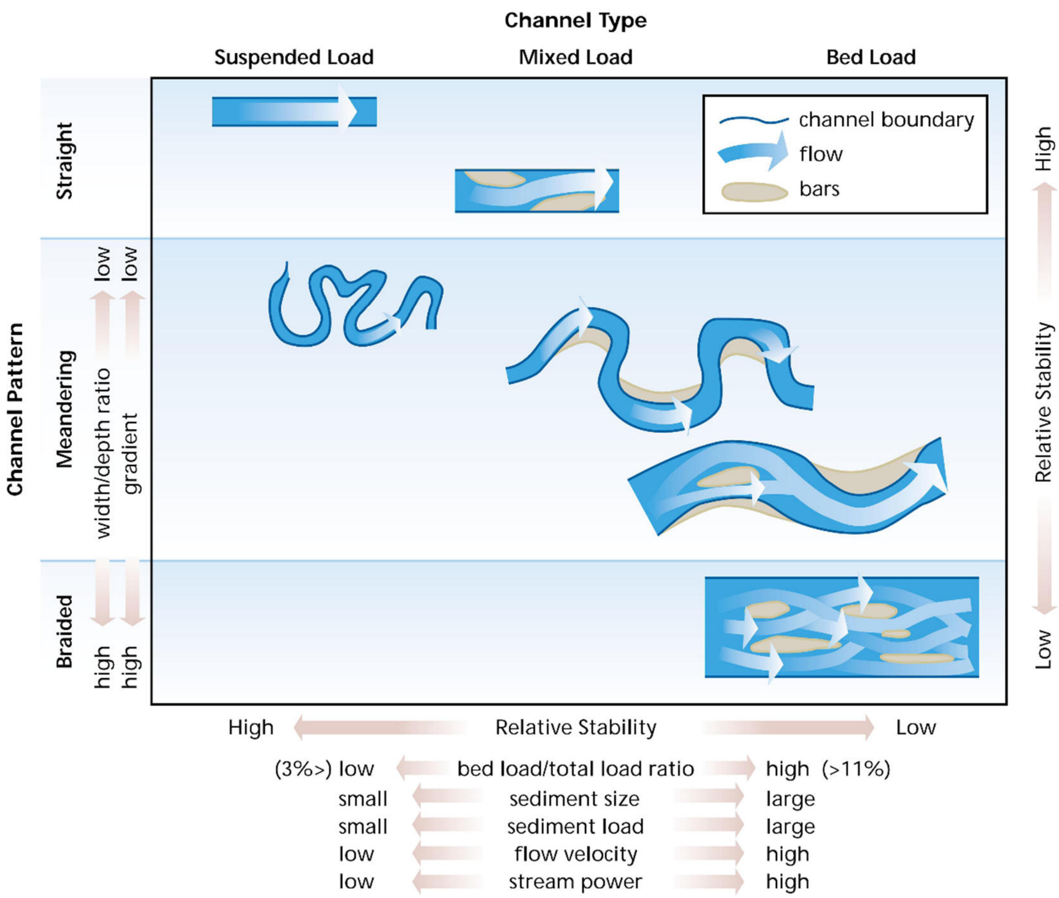

Figure 3.—Classification of channel type and pattern (planform) as a function of sediment size and load ([7] adapted from [11].

Single-threaded channels may be straight due to human alterations or geologic controls (such as bedrock features or a steep valley slope). Sinuous or meandering channels typically maintain their form by eroding the outer bank (cutbank) along the downstream portion of the bend and correspondingly depositing sediment on the inner bank (point bar). Pools are typically formed along the downstream portion of meander bends and riffles (shallow, fast flowing reaches) are maintained between the pools. Progressive erosion and deposition results in meander bend migration both across the floodplain and in the down-valley direction, which is of particular interest to infrastructure design.

Braided streams are dynamic channels whose flow is divided by ephemeral island bars (i.e., deposited sediment, without established woody vegetation) within the active channel. These bars are typically submerged during high flow events, but the majority are exposed during low flow periods. Rapid shifts in channel position, size, and number of bars is typical of braided channels, especially during high flows when the majority of valley bottom may be inundated. The width and transient nature of braided streams can be challenging for stream crossing infrastructure design. Multi-thread stream channels are distinctly different from braided streams, with vegetation maintaining multiple channels and inter-channel islands frequently preserved even during large floods. This type of multi-thread stream can provide habitat heterogeneity and, consequently, high levels of ecological value within stream corridors.

C. Natural Flow Regime

Streamflow quantity and timing are critical to the ecological integrity of stream systems as they control water supply, quality, temperature, channel geomorphology, and habitat diversity. There are five critical components of the flow regime [19]:

1. magnitude
2. frequency
3. duration
4. timing, and
5. rate of change.

Infrastructure in the stream environment can impact all of these five components. Storage reservoirs and flow diversion often have the largest impact on the hydrologic regime as they can substantially reduce high flows and other aspects of the natural flow regime such as low flows and the rate of change of flow. Urbanization typically results in more impervious areas (e.g., roads, parking lots, rooftops) and increased runoff during rainfall and snowmelt. Changes in the flow regime often affect sediment continuity, potentially destabilizing a channel in dynamic equilibrium with its previous water and sediment supply. This can result in a number of responses including channel incision, bed armoring, or aggradation. It can take decades or even centuries for a stream to establish a new dynamic equilibrium in response to a change in flow regime (e.g., downstream of a reservoir), and in some cases it cannot be regained. This leaves the channel in a continuous state of physical and ecological degradation. Even if no adjustments can be made to the altered hydrologic regime, future infrastructure and rehabilitation design can mitigate some of these impacts. For example, if urbanization is increasing flood magnitude and frequency, resulting in channel incision or widening, future infrastructure should be designed for a wider channel and floodplain to convey larger peak flows during floods. A wide flowpath will reduce impediments to flow and sediment transport, and allow for, rather than attempt to control, dynamic channel processes. A riparian buffer could be preserved or incorporated into the design to improve habitat and provide additional bank stabilization during high flows.

D. Riverine Hazards

From the perspective of riverine infrastructure, floods, and the physical response of channels and floodplains to floods, constitute a primary hazard of concern. Most often, the hazards associated with floods relate to inundation and flow velocity. However, streams can cause damage during floods by undermining and eroding banks and valley walls. Hydraulic forces from floodwaters may damage infrastructure (i.e. bridges, diversion dams, and roadway embankments). Other flood-related hazards include stream channel movement, erosion and deposition of sediment in the channel and floodplain, and erosion of adjacent uplands. Channel migration and floodplain transformations during floods may force flood waters to encroach outside of the regulated floodplain and cause damage in unexpected locations.

Floodplains are natural landforms constructed by streams and are periodically and temporarily inundated by floods. Floodplains and stream channels relate to each other through lateral connectivity; during floods both the channel and floodplain convey floodwaters. They serve important hydrologic functions by storing and slowing down floodwaters and attenuating flood peaks. They can also store flood waters as groundwater in alluvial aquifers that can replenish the stream during dry periods. Floodplains are home to riparian habitat which can serve as important corridors and sanctuaries for terrestrial species and serve as food sources and habitat for aquatic species [20, 21, 22]. Floodplains often have regulatory definitions such as the one percent annual chance flood (100-year flood) and floodway. As part of the National Flood Insurance Program, the Federal Emergency Management Agency (FEMA) identifies and maps flood hazard areas. Flood hazard data are used by State and local agencies to regulate development within the floodplain.

Regulated floodplains may or may not completely match the extent of the active floodplain landform and thus may not delineate the full extent of riverine hazards. For example, channel migration and formation of new channels may have historically occurred over a larger area than that which is represented by the regulatory floodplain map. This is why channel migration zones, the area that a channel may occupy or physically influence during a flood, should also be taken into consideration (figure 4). As defined by the State of Washington, a channel migration zone is “the area where the active channel of a stream is prone to move...” or influence the surrounding terrain over a given period of time [23]. Channel migration results from lateral bank erosion and sediment deposition over many years or may occur abruptly in response to a single large flood. During these abrupt transitions, the stream may abandon a side channel, cut off a meander bend, or form a new alignment via a process known as avulsion. When infrastructure limits this natural channel movement, streams may respond by damaging the infrastructure or rapidly eroding other areas. Availability of channel migration zones maps are limited to specific streams in certain States (Colorado, Indiana, Montana, Vermont, and Washington, among others). Channel migration maps should be delineated by trained geomorphologists and can be used in conjunction with inundation hazard maps to fully characterize riverine hazards.

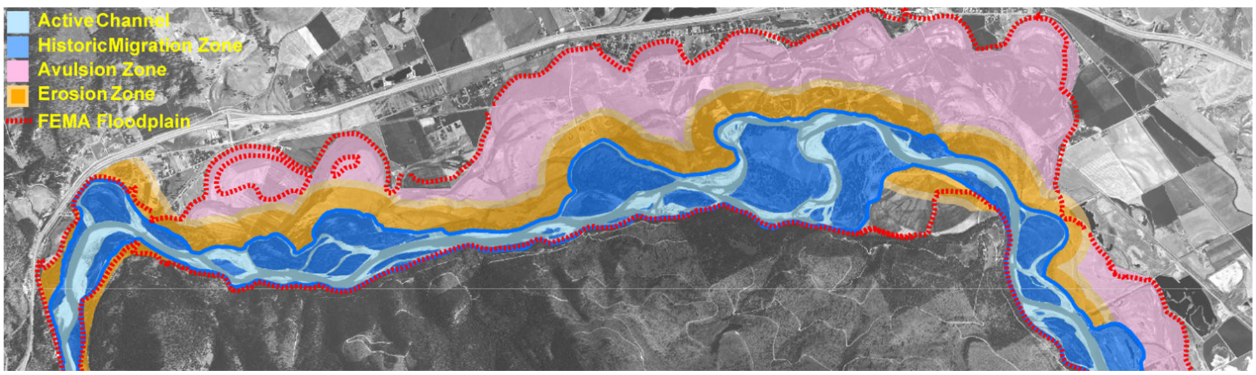

Figure 4.—Example of a channel migration zone study depicting the active channel (light blue), historic channel migration zone (dark blue), future erosion buffer (orange), potential channel avulsion zone (pink), and regulatory floodplain (dashed red line). Clark Fork River, Montana, Applied Geomorphology, Inc., DTM Consulting, Montana State Geographic Information Clearinghouse.

The magnitude and frequency of floods may change over time, often due to urbanization or other land use changes. Urbanization and associated increases in runoff typically amplify the peak flow rate, especially of frequent to moderately frequent flood events (i.e., the 50 to 10 percent annual chance or 2 to 10 year floods [24]). Climate variability and change can also affect flood magnitudes and frequencies. Some areas of the U.S. have seen increases in flood magnitude and frequency over the last century (e.g., the Northeast U.S., [25, 26]) while other areas like the northern Great Plains have seen decreases or no change [26]. Changes in climate associated with global warming are expected to lead to greater magnitude and frequency of extreme weather, but expected trends vary by region and there are large prediction uncertainties [27, 28]. Nevertheless, at a national level, flood prone areas are predicted to increase over the next 80 years over the continental U.S. as a result of climate change [29].

E. Riverine Ecosystems

The ecological health of a stream system is complex and dependent on multiple interactions of a variety of components and processes. Fundamental to ecological theory is the presumption that habitat heterogeneity and biodiversity are directly coupled [30, 31]. Physical complexity in stream form, or "messy streams" provides a diverse range of physical habitat that in turn supports a diverse array of species and their life stages. Messy streams are loosely defined as streams with natural deposits of large woody material, bank erosion in balance with sediment bar deposition, and, where geomorphically-appropriate, multi-threaded planform [32].

The degree of connectivity of water, sediment, wood, and organisms are factors in the ecological health of the riverine system [33, 34]. For example, a flood control project may separate the stream from its floodplain, or a dam with reservoir storage may disrupt the continuity of water and sediment downstream along with the passage of organisms upstream. Water storage infrastructure can reduce the magnitude and frequency of flows. Without larger flow events, fine sediment may accumulate in the interstitial spaces between gravel particles. These spaces are crucial habitat for the macroinvertebrate community and spawning habitat for numerous aquatic species. Dams and reduced flooding also create a barrier for fishes accessing headwater or floodplain habitat for spawning and rearing.

Smaller scale infrastructure such, as riprap-protected banks, decrease lateral connectivity to the floodplain by limiting a river's ability to laterally migrate and generate and maintain dynamic floodplain habitat necessary for many aquatic species life stages. Riprap can also simplify the physical habitat in a stream by encouraging channel incision. For example, armored banks are cited as an important limitation to salmon habitat in the Columbia River Basin [35].

Riparian forests are crucial to the health of riverine ecosystem as they provide connectivity of food and habitat between the terrestrial and aquatic environments. Leaves and wood contributed to streams from riparian forests serve as food for the aquatic insect food base and provide physical habitat for aquatic species. Riparian forests mitigate nonpoint source pollution and impede overland flow into the channel during runoff events. Furthermore, the root system associated with riparian vegetation reinforces stream bank soil, decreasing bank erosion rates. Agriculture and urban development have drastically reduced riparian forest cover in North America which has had adverse effects on water quality and aquatic habitat.

Different types of riverine infrastructure can impact the processes and fluxes that maintain stream ecosystems in multiple ways. Several examples of potential impacts are listed in table 1. Better infrastructure design that considers stream processes and ecosystems can reduce or even eliminate these impacts. Much of today's infrastructure was built when little was understood about the dynamics of streams and their interaction with the floodplain, as well as the ecological importance of maintaining stream dynamics. Thus, many riparian corridors have been removed or ecologically simplified due to agriculture, urban development, channelization, and bank armoring. Fish passage may be blocked by channel-spanning weirs or grade controls, and impacts to roadways and bridges within the channel migration zone are a continuous management concern (figure 5, top).

As aged or damaged infrastructure needs replacement, there is an opportunity to build with more sustainable, resilient, and ecologically-compatible designs (figure 5, bottom). For example, levees and roadways set back from streams and bridges with wider spans permit more dynamic river systems and reduce hazard exposure. Allowing for a wider floodway permits the establishment of vegetation in riparian corridors. Features such as rock ramps can be constructed on or around channel spanning structures such as flow diversion weirs to permit fish passage. The following section discusses how a holistic approach to infrastructure design in the stream environment could be applied to a range of riverine infrastructure types.

Table 1.—Physical Processes Associated with Riverine Infrastructure and Potential Consequences to Infrastructure and Ecosystems

Infrastructure Type	Physical Process	Result of Physical Process	Consequences to Infrastructure and Ecological Impact
Stream Crossing and Channel Infrastructure (dams, diversions, bridges, channelization, culverts, etc.)	**Water impoundment**	• Traps sediment, debris, nutrients, and organisms • Changes in water temperature upstream and downstream • Downstream scour • Changes to flow regime	• Trapped sediment can degrade habitat upstream • Stream environment converted to lake environment • Change in water temperature can impact aquatic species • Migratory fish passage limited or blocked • Channel movement and habitat maintenance from flow and sediment reduced. • Downstream scour can undermine infrastructure
	Flow acceleration **Steeper slope**	• Scours at inlet and outlet • Bed armoring	• Scour pools can compromise the integrity of infrastructure • Scour, break in slope, and fast flow may inhibit passage of fish. • Aquatic habitat impacted from scour and armoring • Downstream deposition may impair infrastructure
	Channelization	• Limits or eliminates lateral channel movement	• Limits natural migration channel processes that create and maintain complex aquatic and riparian habitat. • Can result in upstream migration of headcuts, undermining upstream infrastructure
Streamside and Floodplain Infrastructure (levees, bank stabilization, floodplain development, roads, etc.)	**Bank armoring**	• Limits natural lateral migration of channel • Encourages bed scour and armoring	• May increase bed and bank erosion downstream • Limits natural migration channel processes that create and maintain complex aquatic and riparian habitat. • Reduce native species viability from lack of habitat
	Channel and floodplain fill	• Narrows floodplain or channel • Scours existing channel • Limits natural channel migration • Hydrologic disconnection between channel and floodplain	• Loss of flood storage and flood peak attenuation increases flooding downstream • Increases bed erosion (incision) • Limits natural channel processes that create and maintain aquatic and riparian habitat • Inhibits lateral connectivity between aquatic and riparian ecosystems • Impacts to riparian vegetation that requires floodplain inundation
	Riparian vegetation removal	• Increases bank erosion rates • Reduces shading • Reduces large wood, organic matter, and nutrient inputs to stream ecosystem	• Increases in bank erosion can increase the rate of bank recession, encroaching on private land and compromising infrastructure • Habitat and water quality impacts via enhanced bank erosion and fine sediment inputs • Increases water temperatures and reduces nutrient and organic matter inputs to channel • Less large wood in stream reduces habitat complexity compromising aquatic species life cycles • Inhibits food web connectivity between aquatic and riparian ecosystems

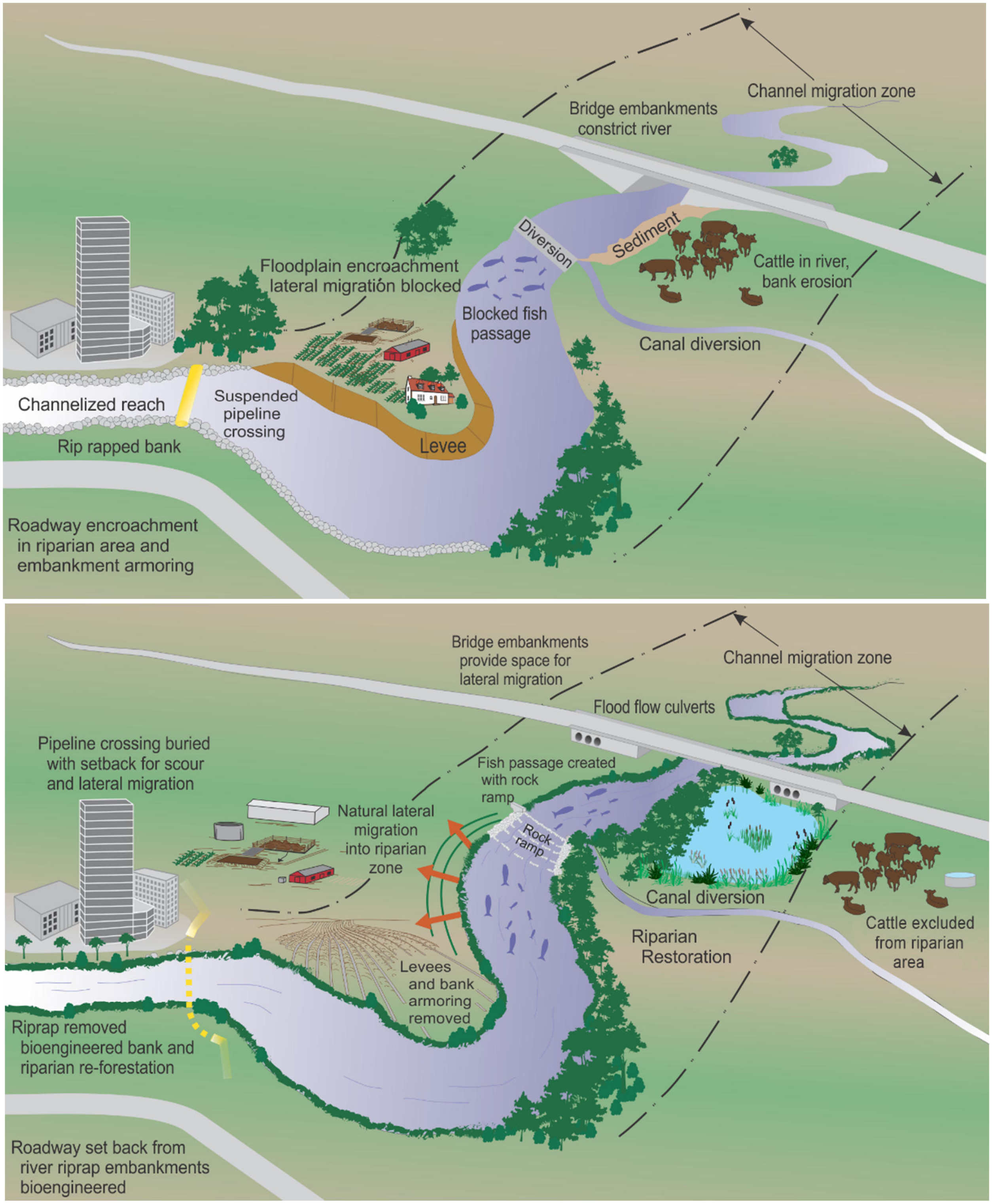

Figure 5.—Illustrations of riverine infrastructure with greater impacts to physical stream processes and ecosystems and greater exposure to riverine hazards (top) and more resilient and stream compatible infrastructure that permits a greater degree of channel movement supporting ecosystem processes (bottom).

III. Managing Riverine Infrastructure

The decision to build new, rebuild, or decommission existing infrastructure is made in the context of many variables. Consideration of the stream environment, its processes, hazards, and ecosystems should play an important role in this decision process. Any decision involving riverine infrastructure, whether it be new or existing, can be made under the sequential framework of first avoiding footprints and impacts within sensitive or hazardous stream environments. Where avoidance is not feasible, minimization of footprints and impacts should be considered, and finally adding mitigation of unavoidable impacts. Opportunities to incorporate ecologically-compatible designs and restore habitat or natural process in conjunction with infrastructure rehabilitation or decommissioning should be considered. This approach largely parallels the existing National Environmental Protection Act (NEPA) [36] and Clean Water Act (CWA) [37] permitting process.

Large infrastructure projects within stream corridors may benefit from master planning that considers infrastructure management within the greater context of a watershed. For example, a road network may suffer from frequent embankment failures due to erosion from streams. Local fixes may ignore watershed-scale trends or problems that a more holistic plan would consider. Long-term maintenance costs may be reduced if planning and repairs occur within the context of a larger plan. Many watersheds have existing plans and studies that identify major water quality and ecological concerns and associated impacts [38]. These studies and master planning documents can help inform how infrastructure management may contribute to or mitigate these impacts. After the devastating 2013 Front Range flood in Colorado, the State supported the development of watershed master plans that evaluated watershed-scale river processes and identified channel and floodplain rehabilitation approaches as well as replacement infrastructure design better suited to stream processes and location within the watershed [39].

A. Decision Tool for Managing Riverine Infrastructure

A framework for considering sustainable and resilient approaches to infrastructure design and management is outlined in the flowchart below (figure 6). The flow chart is divided into four stages:

1. identifying project goals
2. evaluating hazards and values of the project
3. formulating alternatives
4. evaluating alternatives for the decision-making process, and implementation of the project

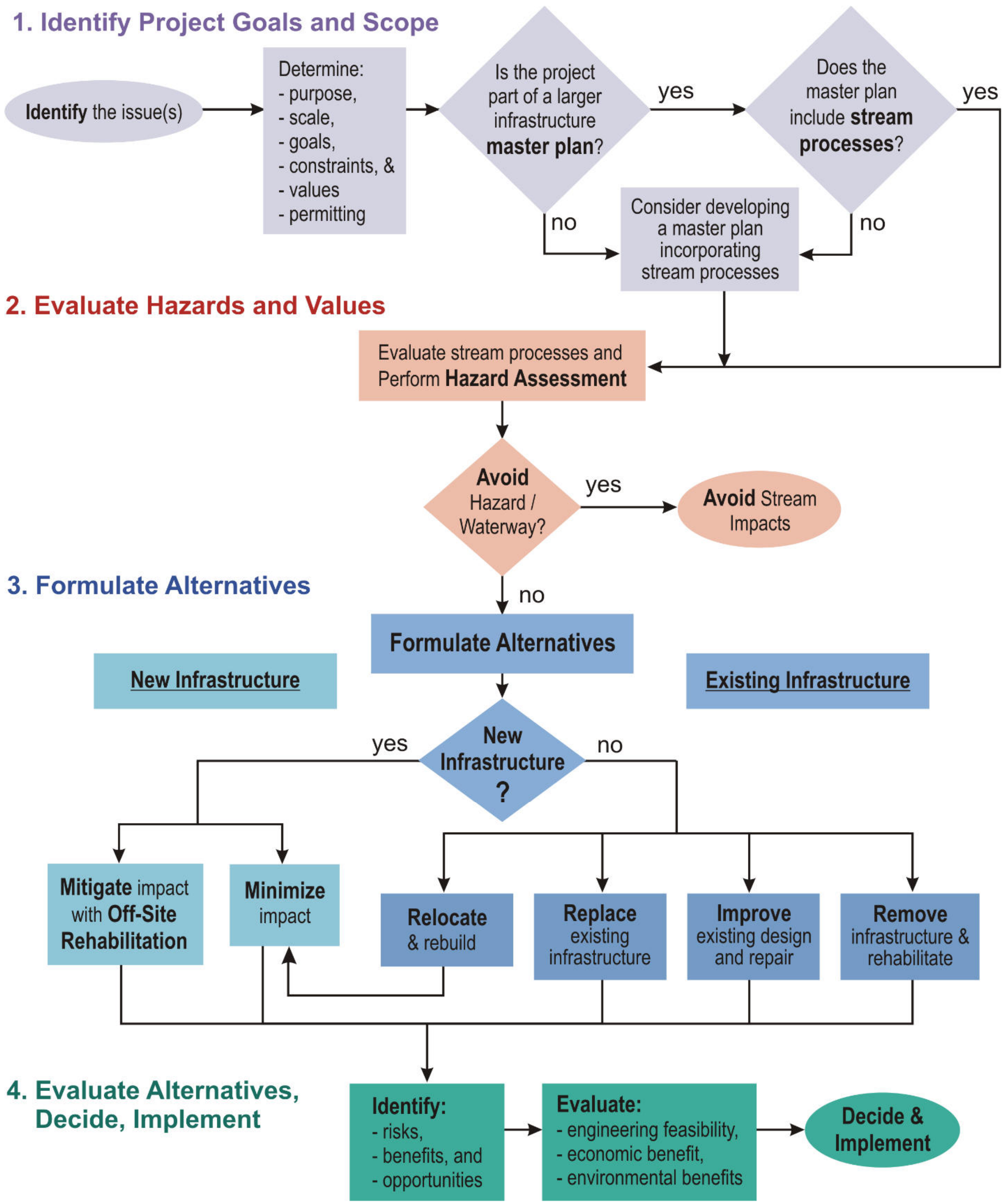

Figure 6.—Decision tool flowchart for managing riverine infrastructure.

Stage 1
At the first stage the following topics should be explicitly identified: project purpose, goals, and scale. These components characterize the physical and geographic scope of the project. Social, economic, and ecological values associated with the project area are typically determined through stakeholder engagement. Stakeholder engagement will assist in identifying not only physical constraints, but also regulatory or social constraints associated with these values. Existing watershed studies or master planning documents may help identify other opportunities and constraints. Such documents can provide the planner with a holistic perspective on the values and stressors associated with a particular stream system.

Stage 2
In the second stage, the project is evaluated in terms of its impacts on the identified values attributed to the stream system as well as the hazards to the project that would be exposed. A hazard assessment should identify how flood inundation hazards, as well as geomorphic hazards associated with stream movement, might impact the planned project. An experienced fluvial geomorphologist is required to perform this assessment.

Stage 3
In the third stage, alternative designs or treatments are formulated. If possible, develop a plan that avoids impacts to the stream corridor. Where impacts cannot be avoided, formulate and evaluate other alternatives. For new infrastructure, minimizing impacts may be possible. Examples include reducing a project footprint in the channel migration zone or lengthening a bridge span. Where ecological impacts are unavoidable, mitigation may be considered, or required, depending on the type of habitat impacted. Mitigating unavoidable hazards should also be considered.

Existing infrastructure poses a different set of considerations. Damaged or old infrastructure may be rehabilitated, replaced, relocated, or removed. An opportunity to restore stream and riparian habitat may exist in conjunction with these efforts. For example, local conservation organizations might partner with irrigation districts to construct fish passage on diversion dams slated for repair after flood damage. Alternatively, replacing a diversion dam with an infiltration gallery may be an option for small flow diversion rates. Removal of obsolete dams can simultaneously eliminate a safety concern and restore aquatic habitat. State and regional wetland mitigation programs may be willing partners in funding such a project (see Box 2) [40]. Relocation placement of infrastructure should be considered with the steps associated with new infrastructure, described above.

Stage 4
In the final stage, alternatives are evaluated in terms of feasibility, costs and benefits (economic, social, and ecological), hazards, and risks. Final decisions may be reached by stakeholder consensus with the aid of decision-making tools such as multi-criteria decision analysis [41].

Box 2. Merrimack Village Dam Removal.
This >100 year old, low-head dam on the Souhegan River, Merrimack, N.H. was owned by a local water utility but not used for supply. Costly repairs were required by the state regulator to mitigate safety concerns. New Hampshire's Dam Removal and Restoration Program offered assistance for dam removal, which the owner opted to do. Removing this obsolete dam restored access to 19 miles to upstream habitat for resident and migratory fish [42]. Tens of thousands of obsolete low-head dams are in existence in the continental U.S. [43]. Removal may be an economical option for managing dams, many of which are in disrepair and a safety concern. Dam removal can result in rapid restoration of habitat for aquatic species.

B. Management Options

Issues pertaining to and solutions for managing the 11 specific types of riverine infrastructure are introduced in this section. These include:

1. floodplain encroachment (general development in the floodplain)
2. large wood management
3. pipelines
4. levees and dikes
5. streambank protection
6. stormwater infrastructure

7. channelized rivers
8. grade control structures
9. transportation infrastructure
10. dams and reservoirs
11. surface water diversions

Channel and floodplain modifications directly or indirectly associated with riverine infrastructure such as channelization, flow modification from upstream flow diversion, storage, or land use change, as well as floodplain encroachment are presented. Management alternatives for streamside and floodplain infrastructure such as roadways, buried pipelines, bank protection measures, and stream crossing or in-channel infrastructure (i.e. bridges and weirs), are also provided. To support these management options, the appendix provides a list of design manuals and guidance documents for managing each type of infrastructure.

1. Floodplain Encroachment and Riparian Management

Floodplain encroachment is any human development occurring within the floodplain that diminishes its capacity to convey floodwaters or limits natural channel migration. Encroachment most commonly occurs with development and associated earthen fill in the floodplains as well as bridge and roadway embankments that cross or parallel a river. Encroachment may also come in the form of levees or dikes built to protect infrastructure from flooding. All of these encroachments serve to reduce the hydrologic and environmental benefits of floodplains and may place infrastructure in hazardous areas. Additionally, floodplain encroachment at one location along a river can increase flood elevations locally and elsewhere downstream. Floodplain encroachment should first be avoided by removing obsolete infrastructure, relocating old or damaged infrastructure, and siting new infrastructure outside of the floodplain. Infrastructure footprints within the floodplain that cannot be avoided should be designed for resiliency to floods. Where impacts must occur, mitigation measures should focus on rehabilitating neighboring floodplains along the same waterbody (figure 7).

Figure 7.—Example of a floodplain rehabilitation on the Poudre River, Fort Collins, Colorado. A levee was removed and a floodplain bench excavated and re-vegetated to hydrologically connect with the incised river. Gravel quarries adjacent to the river were also reclaimed and connected with flood flow paths. Photo: Joel Sholtes, Reclamation.

Riparian corridors generally coincide with floodplains, though they may extend laterally beyond regulated or geomorphic floodplain boundaries. Activities that may not be considered floodplain encroachment—such as clearing riparian vegetation for agriculture, site development, or roadway construction—can reduce or eliminate the ecologic, hydrologic, and physical benefits of an intact riparian buffer. Benefits include retention and filtration of polluted runoff, shading and food sources, riparian and aquatic habitat, bank protection, and sources of wood recruitment for aquatic habitat. Riparian corridor preservation (i.e., conservation easements) and rehabilitation (i.e., re-vegetation) represent cost-effective measures to sustain and enhance stream quality. If riparian impacts are unavoidable, off-site mitigation (preservation and rehabilitation) elsewhere on the stream may be an option.

In some municipalities, counties, and States setback ordinances have been developed to protect stream systems and maintain riparian corridors while also protecting infrastructure, homes, and businesses from flood damage. Guidelines are often developed on the basis of different objectives (i.e. flood protection, wildlife protection, bank erosion control, and water quality concerns), and therefore vary. In an effort to establish easily-understood ordinances, setbacks may range from restricting development in the 100-year floodplain to a fixed setback width from the stream bank (i.e., 100 feet) that may be unrelated to the stream size or location. Development setback approaches based on principles of fluvial geomorphology, such as channel migration rates and extents (e.g., [44]), provide the most accurate estimates of the riparian zone that provides space for the stream to self-adjust, create and maintain riparian ecosystems.

2. *Large Wood Management and Engineering*

Historically, wood was abundant in many of our streams, distributed as individual pieces and in large groups called jams. Streams recruit wood via riparian tree fall, bank erosion, landslides, and with the aid of beavers. As stream corridors developed, large wood transported by floods threatened downstream infrastructure. Log jams impeded navigation in large river systems [45] or accumulated upstream of infrastructure (i.e., bridges, irrigation turnouts, etc.). Prioritization of navigation and flood conveyance led to the removal of wood. Additionally, agriculture and urban development resulted in the loss of riparian forests. In forested watersheds, logging practices and log removal methods often cleared streams of wood that prevented natural recruitment [46].

Recent research on the role of wood in stream systems has highlighted the crucial ecological and physical role it plays in the health of rivers in forested landscapes [47]. This is evident in the scientific community's effort to discontinue the use of the phrase "large woody debris" in favor of the less pejorative "large wood". It is also evident in the growing understanding that "messy streams" are healthy streams [48]. Large wood in streams can help trap sediment. The dynamic hydraulic patterns large wood creates sort sediment, providing diverse habitat including spawning beds (figure 8), pool habitat, slack water for fish, and shade to moderate water temperature [49]. Furthermore, wood accumulation can influence a stream channel's size, planform, and slope, promoting physical heterogeneity and ecological diversity [50, 51, 52, 53].

Current stream rehabilitation practice recognizes the benefit of wood placement where natural woods jams and riparian forests have been removed [54]. Placing wood in urban streams has demonstrated some limited ability to restore physical habitat where watershed-scale stressors do not overwhelm the benefits [55]. However, if large pieces mobilize, they can threaten downstream infrastructure such as bridges and culverts through clogging flow paths and enhancing scour. Various Federal, State, Tribal, and local agencies are promoting the careful use of wood in stream and habitat rehabilitation efforts. Wood used in stream rehabilitation can be a more cost-effective and ecologically beneficial approach over stone materials and can serve the rehabilitation process by recruiting more wood. Wood structures can be designed for a variety of situations and longevities by understanding the geomorphology, hydraulics, and geotechnical aspects of a project. In many situations it may be desirable to place both stable and dynamic wood structures, though dynamic wood structures may not be desirable upstream of vulnerable infrastructure such as bridges. To restore natural wood recruitment, riparian forests should be protected and restored and bank protection removed where feasible so that the large wood supply is naturally maintained.

The Large Wood National Manual, published by Reclamation and the U.S. Army Corps of Engineers [56] establishes methods to assess, design, and manage wood in stream and stream rehabilitation projects in the U.S. Other guidance on managing large wood in streams is available where impacts to riverine infrastructure are a concern [48, 57]. This guidance can aid managers in deciding on when to leave wood in rivers and how to mitigate risk where riverine infrastructure may be impacted. Current challenges in utilizing large wood in channel and habitat rehabilitation centers propose the debate of how stable or dynamic these features should be (i.e., level of anchoring and design flood stability) and identifying acceptable levels of wood movement in developed river corridors.

Figure 8.—Top: A pile-supported engineered log jam can increase water surface elevation immediately upstream, creating a pool for aquatic species, influencing the distribution of shear stress in Elwha River, Washington. Photo: Jennifer Bountry, Reclamation. Bottom: Large wood accumulation on a mid-channel island during spring runoff on the Methow River, Washington. Photo: Reclamation.

3. Pipelines

Buried pipelines transporting water, waste water, fossil fuels, and hazardous chemicals crisscross the U.S. Oil and gas pipelines account for some 1.7 million miles of buried pipeline [58], with water and sewer pipelines far exceeding this length. Inevitably, these lines cross or parallel streams. As described above, streams may migrate laterally or the bed may lower due to erosion (scour) during floods, which can expose pipes and result in damage and spills (figure 9), which can have both short- and long-term adverse impacts to water quality, fish and other aquatic organisms, and aquatic habitat. This happened when the Yellowstone River eroded its bed during a four percent to two percent annual chance flood (25 to 50-year recurrence interval) exposing an oil pipeline that subsequently ruptured from the hydraulic forces of the flow. In addition to vertical scour and lateral migration resulting from floods, streams may also adjust to land use and hydrologic changes over a longer period of time. A classic example of this occurs in urban areas where water and sewer lines, buried several feet below a channel bed, become exposed and perched over a period of decades. Streams incise vertically and widen in response to the increasingly erosive energy of floods in urban watersheds exposing the pipeline. This follows the channel evolution model, as depicted in figure 2.

Pipelines may be buried under waterways or bridged over them. Bridged pipelines are only subject to vertical scour concerns if their stabilizing features (abutments and piers) are at risk of being undermined. Both lateral stream migration and vertical scour can impact bridge piers and abutments. The channel migration zone should be considered when designing both pipeline bridges and

Figure 9.—Formerly buried pipeline exposed by gully incision (note headcut in lower left) in a desert wash, Navajo Reservation, New Mexico. Photo: Michael Sixta, Reclamation.

buried pipelines. An appropriate burial depth and setback width relies on knowledge of geomorphic processes including how often the stream floods and how susceptible the bed and banks are to erosion. Total potential vertical scour depth should take into account local, temporary scour resulting from passing floods, as well as long-term channel incision resulting from channel adjustment to some disturbance. Lateral setbacks should account for the channel migration zone. Safety factors should also be applied when estimating vertical and lateral setbacks. For buried pipelines, the elevation of the total scour depth, including a safety factor, should then be extended across the entire channel migration zone because the channel bottom may occupy this area at some point in the future. In addition to appropriate setbacks and burial depths, safety valves and other above-ground, emergency shutoff infrastructure should be sited outside of the influence of flood waters. Pipeline operators should regularly evaluate the risk of pipeline exposure at stream crossings, especially after flood events. Refer to the *Pipeline and Hazardous Materials Safety Administration's Advisory Bulletin ADB–2016–01* [59] for a complete checklist of items to consider for reducing flood-related hazards at stream crossings.

4. Levees and Dikes

Levees, embankments, and dikes are often constructed to protect other floodplain infrastructure and land uses from inundation and erosion. This infrastructure has allowed for economic development in flood prone areas, while reducing risks to people and property for the common floods. Some levees are constructed and maintained by the U.S. Army Corps of Engineers; however, the majority of levees have been built by State, local, and private entities and may or may not be actively maintained [60]. Although levees can provide social and economic benefits, they also affect flow and sediment transport within stream corridors, disconnect the stream channel from its floodplain, limit natural channel migration, and can magnify the peak stage and erosive force of large floods. Because levees disconnect the channel from its floodplain they eliminate the ecosystem function that the floodplains provide. Additionally, levees do not guarantee flood protection; a range of factors such as historic levee design, land use change upstream, and level of maintenance can lead to a higher or lower level of flood protection. Hence, levees can have detrimental consequences to both the environment and, when they fail, to infrastructure as well.

Levees can reduce flood attenuation and concentrate a higher proportion of flood flows within the channel by reducing or eliminating floodplain conveyance. As a result, a given flood event may have a higher peak flow and flood stage locally and downstream, exerting higher stresses on the channel boundary and levee toe. This can result in vertical channel incision, which may degrade habitat, alter bed sediment, and change the sediment flux downstream. For example, the lower Mississippi River has experienced increased flood stage for the same flood discharges over time due to a variety of engineering works, including increased levee construction. The 1993 flood stage at St. Louis would have been 10 foot lower if not for the presence of engineered flood control efforts upstream including levees [61]. Streams naturally migrate, which can compromise the structural integrity of levees and increase risk of breaching. In addition to river migration, seepage, animal burrowing, and overtopping by flood waters are other levee failure mechanisms. When levees breach during floods, widespread damage to property and infrastructure may occur.

When a new levee is proposed, the design team should first analyze the current site conditions within the channel and adjacent floodplain. Assessments should also consider historical migration patterns and potential future river alignments. Depending on the site, it may be more economical to move the infrastructure within the flood prone area rather than constructing a levee system. Where infrastructure cannot be moved and constructing a new levee is unavoidable, levee design height and alignment are typically dictated by flood protection requirements. Where feasible, building the levee outside of the channel migration zone is recommended to allow for natural and controlled channel migration (figure 10). Levee systems constructed outside of the channel migration zone will have a lower failure risk and require less maintenance because the stream channel will be less likely to physically influence the levee. To further decrease the erosion risk at the levee toe, protective measures can be installed at the toe of the bank.

An existing levee system in need of repair or replacement may provide an opportunity for reconstructing the levee at a location set back from the channel or breaching it in conjunction with channel and floodplain rehabilitation. In their Room for the River Program, the Netherlands flood agency bought out private lands and set back levees to increase the flood storage capacity of their rivers and reduce flood stages in lieu of building more and higher levees. This provided opportunities to improve the environmental quality of their rivers and floodplains and enhance flood protection for approximately 4 million people [62]. More than 30 projects have been completed under this program to expand the floodplain, increase flood conveyance, and restore natural riverine processes. Sustainable and resilient levee systems require a comprehensive evaluation of levee safety (structural integrity and contemporary level of protection) and flood protection priorities that consider both social and ecological resources [63].

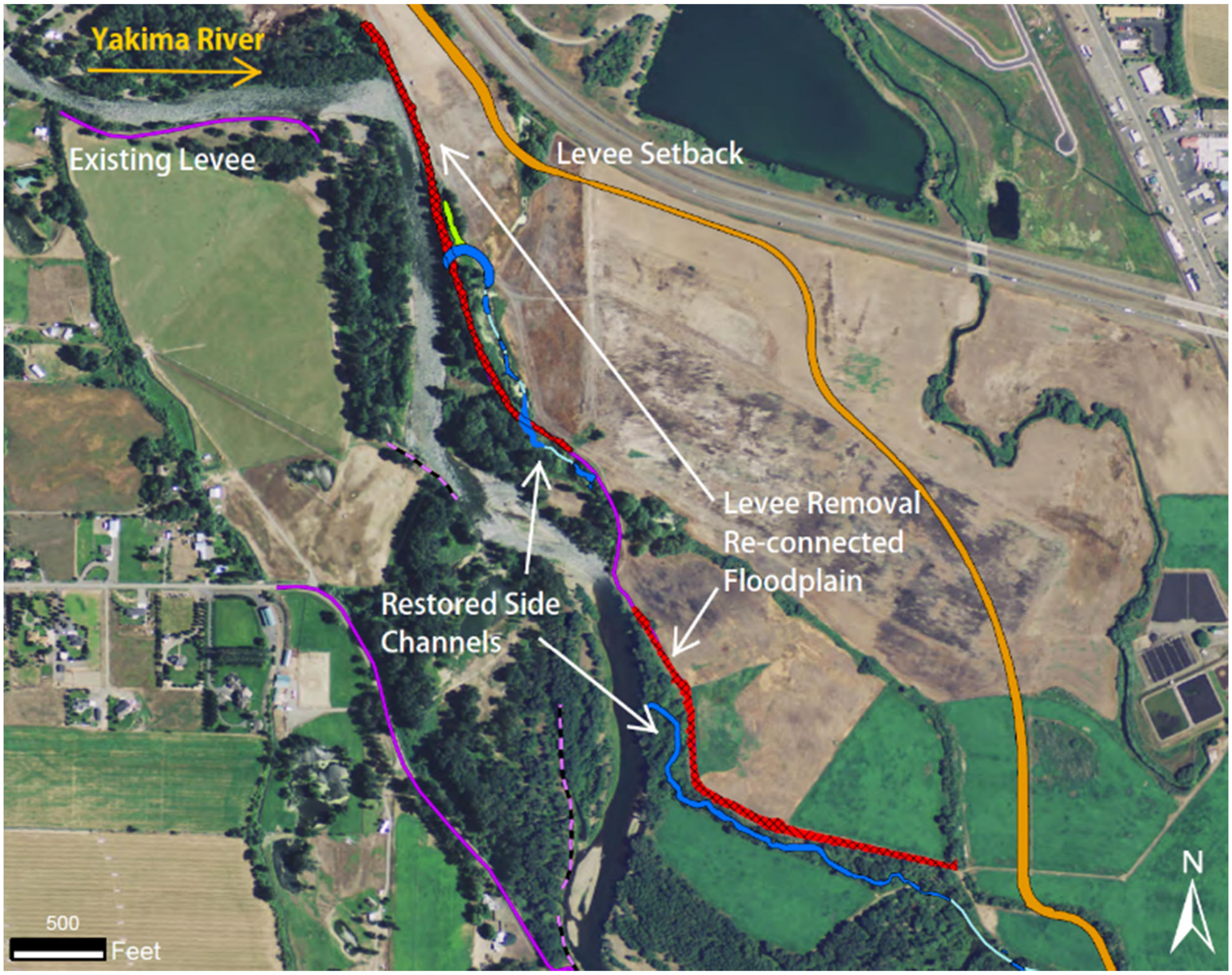

Figure 10.—An example of a proposed levee setback and side-channel rehabilitation project on the Yakima River, Washington. Hydrologic connection restored to western floodplain. Map courtesy of Robert Hilldale, Bureau of Reclamation. Setback alignment still under discussion.

5. Streambank Protection

Streambank migration is a result of fluvial erosion of the streambank. When erosion leads to over steepened banks, bank failure or collapse can occur, which is a geotechnical process. Streambank migration is a natural process and important in maintaining habitat diversity within a stream corridor. In unstable channels adjusting to a disturbance, bank erosion may be a symptom of channel adjustment, such as bank failure, following channel incision (figure 2). Stream bank erosion can be exacerbated by changes in runoff hydrology due to land use change, and direct modifications such as removal of bank vegetation. Where natural channel migration threatens important infrastructure, or where bank erosion and mass wasting in unstable, channels represent a water quality and habitat impairment concern; stream bank protection and stabilization may be warranted.

Streambank protection and stabilization encompasses a wide range of strategies for reducing bank erosion and stabilizing over-steepened and unstable stream banks. Bank protection refers to practices that serve to reduce scour and limit bank erosion. Bank stabilization refers to geotechnical practices that enhance bank stability against bank failure. Streambank protection and stabilization design should focus on incorporating natural and living materials and minimizing the use of hard materials to improve the sustainability and ecological benefits of bank stabilization projects [64].

Three primary approaches to streambank protection are:

1. traditional engineering
2. bioengineering
3. flow deflection

Often, a combination of techniques is used within a particular project. The traditional engineering approach to streambank protection involves rock riprap, concrete blocks, or other manufactured materials. Hard engineering approaches are often the most effective protection measures at the toe of eroding banks and a reliable technique when immediate performance is critical. However, hard engineering approaches may require continual maintenance and also result in substantial ecological impacts due to the homogenization of stream reaches and removal of riparian vegetation. Additionally, unprotected reaches downstream of armored reaches can be more susceptible to erosion.

Streambank bioengineering is an approach defined as the use of live and dead woody materials in combination with natural and synthetic support materials for slope stabilization, erosion reduction, and vegetative establishment [65]. Bioengineering most often requires a hardened toe section for stability, which could be constructed from large woody material or rock (figure 11). Bank stabilization involves increasing the tensile strength of the bank material by planting woody vegetation with deep roots and increasing the bank material slope safety factor via drainage or physically reducing the bank slope. Techniques that are part of a traditional engineering approach can be altered or enhanced to provide habitat benefits. For example, bank stabilization systems composed of living plant materials can be used in association with inert materials, such as wood, rock, or manufactured products.

Flow deflection includes a wide variety of treatments that can be utilized to divert flow away from the eroding banks and promote deposition. Examples of flow deflection devices include: bendway weirs, bank vanes, spurs, and engineered log jams [64].

Some bank erosion and failure can be ecologically beneficial. Streams that exhibit chronic bank failures may be incised significantly reducing their habitat and ecosystem benefits [18]. Channel rehabilitation and grade control may be necessary in conjunction with bank protection and stabilization. Before stabilizing banks, it is recommended to evaluate moving infrastructure back from stream banks as a long-term benefit to the infrastructure and environment.

Figure 11.—Example of streambank bioengineering (right side of pictures) with riprapped bank (left side of pictures) in first year of construction (left) and two years later (right). Credit: Natural Resources Conservation Service.

6. Stormwater Infrastructure

Stormwater runoff can adversely impact the quality of natural water bodies and physically degrade the channel supplying and receiving the flow. This is due to both magnified peaks and larger runoff volumes, along with contamination associated with human activities. The changes in runoff regime to streams is called hydromodification [13]; these impacts result in what is referred to as the “urban stream syndrome” [67]. The quality of stormwater can be impacted as runoff picks up pollutants from streets, parking lots, and the general urban landscape. Pollutants include such things as bacteria and viruses associated with animal and human waste, litter, road salt, pesticides, fertilizers, oil, and fine sediment. The amount of pollutants entering stormwater can be reduced by preventing their release into the environment, temporarily containing and treating stormwater in retention ponds, or sending stormwater through wetlands or sand and gravel filters before discharging to a waterbody (figure 12).

Stormwater runoff entering a stream channel can lead to local scour and degradation of the stream channel receiving stormwater. Local scour may occur if stormwater enters the receiving channel with high energy or velocity. Energy dissipation structures can reduce the potential for local scour at stormwater outfalls (figure 12). Larger scale channel degradation (incision and widening) may occur if the rate of stormwater discharge significantly increases the flow rate in the receiving channel. This degradation can impact other riverine infrastructure such as bridges and buried or adjacent pipelines. It can also exacerbate bank erosion. The potential for channel degradation can be reduced by creating infiltration areas (sand and gravel areas and permeable pavements) and flood detention areas that attenuate the peak discharge rate. Care should be given in designing detention areas and outlet structures to avoid extending the runoff hydrograph at a lower, though still erosive rate [68].

In many urban settings, the stream channel receiving stormwater has already degraded and is lower than its tributaries. Streambed grade control on the tributary streams supplying stormwater can prevent degradation from migrating upstream along a tributary. Channel rehabilitation may also address reach-scale channel stability and habitat degradation concerns. However, habitat rehabilitation in urban environments may be limited where hydromodification and water quality impacts are not able to be addressed at the reach scale.

Figure 12.—Left: A sand and gravel filter was used to clean urban stormwater from a parking lot along the South Platte River near Denver, Colorado. Right: Stormwater and tributary baseflow are discharged through a scenic grade control and energy dissipation structure just before entering the South Platte River in Denver, Colorado. Photos: Tim Randle, Reclamation.

7. Channelized Rivers

Stream channelization (the straightening and shortening of a reach of river) was widely practiced in the 20th century as a local flood control measure and a means to drain riparian wetlands for farming. Scientific research and experience have made a strong case against channelization in most circumstances [69]. Though channelization may reduce flooding locally, channelized reaches route flood flows more quickly increasing flooding downstream [70]. Channelization increases the local channel slope by shortening a reach over the same drop in elevation. This local steepening often results in channel incision and widening following the channel evolution model, developed in part from observations of channelized streams (figure 2), [11, 71].

A slow reversal of stream channelization began in the latter part of the 20th century and continues today. Previously-channelized reaches are being restored to satisfy goals for habitat and channel stability. A well-known example is the Kissimmee River Restoration Project in Central Florida (figure 13) [72]. Rehabilitation of channelized reaches may involve plugging the channelized reach, restoring connection with the historic channel, or excavating a new channel with greater sinuosity. Where resources or land are not available to change the planform of a channelized reach, in-channel structures may introduce some physical complexity, meet channel stability goals, and, to a limited extent, improve habitat. Examples include Newbury riffles (weirs) and engineered wood [73]. New channel design should consider appropriate design discharges [74], sediment supply from upstream, channel bed mobility, and geomorphically-appropriate cross section dimensions, channel planform and longitudinal profile [75, 76].

Figure 13.—Channelized reach of Kissimmee River (left) [77], and restored reach with meandering planform and channelized Reach Filled (Right) [78].

8. Grade Control Structures

Grade control structures are typically constructed in channels that are experiencing incision. Channel incision progresses from downstream to upstream and serves to lower channel slope in response to disturbances including increased runoff from urbanization, channel constriction by infrastructure, reduction of sediment supply due to a reservoir, or increased slope from channelization. Following channel incision, overly-steepened and heightened banks frequently fail and introduce fine sediment to the stream, resulting in a widening stream as described by the channel evolution model (figure 2). Channel incision can also draw down the groundwater table, leading to die off of riparian vegetation [79]. A series of low head grade control structures can serve to reduce the slope of a channel between the structures and reduce or halt incision. However, their success in halting erosion is mixed and their adverse impacts on the upstream passage of aquatic organisms is well documented [80].

Other concerns with grade control structures include promoting unplanned lateral migration around the structures (flanking), downstream scour, and local bank erosion. Mitigation measures for these problems include installing more frequent structures with reduced height, providing flanking protection (tie-in behind banks and into floodplain), or rehabilitating the structures as ramps to provide for fish passage. Maintenance for most types of grade controls often includes periodic replacement of dislodged rock and additional flanking protection.

Grade controls should be designed and constructed appropriately for the channel type and geomorphic context. For example, building weirs or step structures such as cross vanes in mild-sloped streams with fine bed material size is out of geomorphic context and not sustainable. Where practical and appropriate, sheet pile, gabion, and grouted grade control structures can be masked by natural and local materials, such as wood and loose stone. Multiple lower height grade control structures are generally preferred over a few larger structures [81]. For conditions where channel incision is very likely, but not yet occurred, an armored bed that resists entrainment, thus preventing incision, may be used. Because channel incision progresses upstream, ensuring that grade control structures will not be undermined from below is an important design consideration. Ramp type grade control structures can be used where lower slopes are needed for aquatic organism passage. Rock drop structures may be most applicable in steeper, step-pool channels as they simulate natural geomorphic conditions.

9. Transportation Infrastructure – Roads and Bridges

Roads are a critical part of our Nation's infrastructure. With typical planning and design approaches, roads inevitably cross or parallel streams and rivers. As a result, it should be expected that the functions of stream corridors will be impacted by roads. Roads impact stream corridors hydrologically, geomorphically, chemically, and ultimately ecologically. However, roadway location, design, and repairs can be conducted in a manner to reduce or eliminate these impacts.

The impervious surfaces of roadways generate more runoff than undisturbed land. They also serve to concentrate runoff that they intercept and divert from what would normally be diffuse overland and shallow groundwater flow. Roads and associated drainage structures discharge the concentrated flow onto hillslopes where new channels can be eroded, or directly into existing channels. Subsequent degradation of receiving channels, new channel creation, and sediment from unpaved roads can increase sediment loads to receiving waters, leading to water quality and habitat impairments associated with increased turbidity and fine sediment loads, as well as channel instability.

The presence of roads in the stream corridor can potentially limit natural channel movement and changes. Fill for roadway embankments adjacent to streams can hydrologically disconnect channels from their floodplains and limit overbank flows during floods, thereby increasing flow velocity and erosive potential to the channel banks, beds, and remaining floodplains. Finally, natural channel movement, important from an ecological standpoint, is typically curtailed or reversed near roadways with embankments and channelization.

Figure 14.—Examples of the consequences of undersized stream crossing infrastructure: A) large plunge pool and elevation drop at outlet of undersized road crossing or as a result of channel incision; B) sediment deposition at inlet of undersized culvert; C) a culvert (span 5 m (meters), height 2.9 m) was built in the early 1950s and crosses a stream with a width of 9 to 10 m; D) the culvert was replaced with a bridge (span 30 m), much wider than the channel. Photos: Daniel Cenderelli, U.S. Forest Service.

Vehicles traveling on roadways can transport hazardous chemicals. Leaks occurring through accidental spills or poor maintenance, as well as heavy metals deposited in dust, can enter the stream environment via stormwater runoff. In addition, ice removal and dust reduction chemicals frequently wash off of roads and impair water quality.

Streams are important corridors for wildlife that travel along and to streams. The presence of roads can impact wildlife indirectly through habitat loss and fragmentation. Vehicles can also increase risk of injury or death from collisions.

Providing for safe access between streams and uplands over or under roadways can help alleviate these impacts.

Roadways in the stream corridor can be managed to reduce or even avoid many of the above impacts. Existing road infrastructure can be retro-fitted to reduce the impacts of stormwater via better drainage design and energy dissipation. Roadway decommissioning on Federal lands can remove under-utilized roads from use, reduce maintenance costs, and mitigate the sediment concerns described above. When floods damage roadways, an opportunity exists to improve upon the previous design. Improvements may include setbacks from the stream or bioengineered bank stabilization measures that incorporate vegetation (Box 1). New roadway design can site alignments closer to or along valley margins and away from environmentally sensitive and potentially hazardous floodplains. Thought potentially more costly upfront, many of these approaches can reduce roadway maintenance costs and pay for themselves [82].

Any structure that crosses a stream, such as a bridge or culvert, has the potential to alter flow hydraulics, channel substrate conditions, and the downstream transport of sediment and wood. The degree of alteration is most pronounced in crossings that are considerably narrower than the natural channel width upstream and downstream of the crossing. Road-stream crossing structures that are narrower can cause upstream backwatering of the structure inlet during floods. This, in turn, can result in stream crossing failure. This backwater can also cause sediment and debris to be deposited upstream of the inlet. Accumulated material at the inlet can lead to frequent maintenance or a road failure that disrupts the transportation system, reduces water quality, and degrades channel conditions (figure 14a). Road-stream crossings with culverts that are narrower than the natural channel increase flow velocities through the structure at high flows. The high velocity of flow exiting the culvert outlet deepens and widens the channel immediately downstream of the outlet, forming a drop or perch at the culvert outlet, and impeding the upstream migration of fish and other aquatic organisms (figure 14b).

The “stream simulation” approach to designing road-stream crossings integrates fluvial geomorphology concepts with engineering principles to design a natural and dynamic channel through a structure that has similar channel characteristics as those in the adjacent natural channel [83]. By developing a design channel through a road-stream crossing structure with a gradient, cross-section shape, and sediment size characteristics that are similar to a stable nearby reach, natural fluvial processes will function through the structure and provide unimpeded passage for fish and other aquatic organisms. The bridge or culvert is designed around and over the stream simulation channel: the dimensions of the channel determine the dimensions of the structure (span, depth of embedment, height). This means that the width of a stream simulation design structure is equivalent to or exceeds the bankfull width of the natural channel, which reduces or eliminates backwatering or ponding at the inlet during moderate floods and makes those areas less prone to sediment and debris accumulation. Caution should be given to not over-widening the channel when installing culverts, which can lead to sedimentation and vegetation growth upstream [84]. This is why maintaining a continuous channel through the crossing is important. Stream simulation structures are less susceptible to damage by high flows and debris blockage because flows are not constricted until they substantially exceed bankfull flow conditions (figure 14d).

Channels with wide, active floodplains that are frequently inundated and convey a large percentage of flow when discharge exceed bankfull may require floodplain relief culverts through roadway fill (figure 5, bottom). These culverts reduce the amount of flow being funneled through the channel crossing and allow hydrologic floodplain connection downstream. These design solutions will allow the stream simulation channel and floodplain to function more like the adjacent stream. In areas where surface runoff is not channelized, such as washes in arid regions or wet meadows and sloughs, concentrating runoff into one culvert can result in the creation of an incised channel and grade control concerns downstream. Crossing design that allows for diffuse flow such as porous embankment fill or multiple culverts across the wider surface drainage path can mitigation this impact and result in more resilient infrastructure.

Where to cross a stream and how to orient the crossing structure are also important design considerations. Where possible, crossings should not be located at channel bends as they prevent the channel from migrating and can lead to bank and embankment erosion problems over the long-term.

10. Dams and Reservoirs

Dams are designed and constructed to create reservoir pools for a wide variety of purposes including municipal and industrial water supply, irrigation, flood control, hydropower, recreation, and providing downstream minimum flows for navigation and water quality. As of 2016, there are 90,580 “large” (> 6 m) dams in the U.S. according to the National Inventory of Dams [85]. There are hundreds of thousands (perhaps millions) of additional smaller dams or other water impounding structures not documented by this inventory.

Dams and reservoirs affect streams in a number of ways. They act as barriers to fish and other aquatic organisms that travel up and down streams as part of their life cycle [86, 87]. Deep reservoirs can release water downstream with temperatures much colder than what would normally occur. The colder water often released from reservoirs tends to favor non-native fishes over native [88, 89]. Dams can also affect stream channels by changing the quantity and timing of stream flows and by trapping sediments from the watershed. Diverted flows reduce floods downstream that may have helped maintain important aquatic and riparian habitat [90, 19]. Flow releases tied to hydropower generation can vary dramatically over the course of a day or week, impacting aquatic species, such as insects, that evolved under more gradual changes in water level [91, 92]. Such rapid fluctuations can also cause streambank instability.

Reservoirs behind dams tend to trap sediment transported by inflowing streams. Reservoir sedimentation is often incorporated into the design, but can become problematic as sediment reduces the storage capacity of the reservoir and clogs intake structures. In reservoirs that trap the majority of incoming sediment, clear, sediment-free water released downstream can erode the channel until either the stream bed is armored with gravel and cobbles, or the longitudinal channel slope reaches a new, milder equilibrium via incision, or both. Floodplains can become disconnected (less frequently inundated) from the incised stream channel.

Environmental impacts of dams can be mitigated through a variety of actions:

- establishing minimum stream flows for aquatic habitat,
- providing periodic high flows to reset and restore habitat,
- releasing water from different reservoir elevations to achieve the desired water temperature,
- providing fish passage infrastructure,
- passing the upstream sediment supply through or around the reservoir, and
- dam removal.

Available sediment loads to the downstream channel should be considered when developing plans to change reservoir operations. More high flows without sufficient sediment can lead to additional channel erosion. A long-term sustainable goal for reservoir management is to pass sediments to the downstream channel each year in a quantity approximately equal to the mass or volume of sediments entering the reservoir and, to the extent possible, with similar timing [93].

Although dams serve many useful purposes, they occasionally need to be removed for a variety of reasons, including fish passage, safety concerns, obsolescence, or the reservoir has filled with sediment. When dams are removed, special consideration may be needed for the sediments that have been trapped within the reservoirs. The potential impact of these reservoir sediments during and after dam removal can range from negligible to very significant, but the downstream effects are temporary (days to years) [94].

11. Surface Water Diversions

Water is commonly diverted from stream channels for agricultural, municipal, and industrial use, for navigation, and for hydropower with low elevation ($\leq$ 6 m) diversion dams or weirs. These diversion structures locally raise the stream water surface so that water can be diverted into canals, tunnels, or pipelines. Small diversion structures may trap some sediment upstream, but typically do not disrupt sediment continuity or natural flow regime beyond a local scale [95]. However, these diversions can block passage for fish and boats, and create safety problems for recreationists. Excessive water diversion, especially during low flow seasons, can result in elevated water temperatures and impact water quality for aquatic organisms downstream [96].

Careful engineering is needed to limit the diversion of water to the desired flow rate and, to the extent possible, exclude the diversion of sediment, wood, and trash into water conveyance infrastructure. Diverting water from near the surface of the stream can avoid the diversion of coarse sediments, which travel along and near the stream bed. Installing trash racks can exclude wood and trash, and fish screens can be installed to prevent the diversion of fish. Appropriately positioning the diversion inlet and weir along a stream is an important consideration. Not accounting for natural bank erosion as well as the lateral distribution of sediment within a stream reach can adversely impact water diversion and distribution infrastructure and increase maintenance costs.

Different methods exist for mitigating the impacts of diversion structures on streams. Rock ramps leading up to diversions can be constructed to allow fish and boat passage and reduce safety concerns. Where land is available, bypass channels constructed around diversions can also be effective solutions for passage concerns. Diversion weirs can be constructed from natural boulder and cobble material that can be adjusted as streams migrate and can be repaired after floods more readily than concrete-based infrastructure (figure 15).

Wells and infiltration galleries can be used to divert surface water from streams at lower flow rates (< 10 ft^3/s). Wells are constructed near the stream channel. Infiltration galleries are horizontal wells under the streambed. Pumps and additional energy may be necessary to divert water through wells and infiltration galleries. These diversion strategies can be very effective at diverting water without diverting sediment, wood, trash, or fish, which can reduce costs for water treatment, maintenance of conveyance infrastructure, and eliminate the need for trash racks and fish screens. They also have the added benefit of not blocking passage for fish and boats, more accurately diverting water, and reducing overall diversion impacts on the stream.

Figure 15.—Left: A low-head diversion weir constructed from natural, non-grouted materials replaced a push-up dam on the North Fork of the Gunnison River, Colorado. It allows for fish and boater passage and provides a low-maintenance solution for water diversion. Right: A bypass channel constructed around Howland Dam, Maine, for migratory fishes. Photos: Jeff Crane, Crane and Associates, Inc. (left) and Google Earth (right).

C. Managing Riverine Infrastructure under Uncertainty

Infrastructure design in stream environments often relies on estimates of design flows and sediment yield. These estimates are inevitably subject to uncertainty due to an imperfect or relatively short data record, uncertainty in deterministic modelling, as well as changing hydrology under climate and land use change. Short term historical records may limit the accuracy of predictions of extreme events to inform design. Uncertainty in hydrologic and hydraulic models can cascade resulting in a wide range of predicted conditions. Finally, temporal changes in hydrology due to land use change, namely urbanization, or changes in climate, may invalidate inferences about the future drawn from historic data. Faced with these uncertainties, managers may opt to take traditional routes for managing uncertainty such as applying a safety factor for more conservative design. However, this may result in less ecologically-compatible results. Other approaches for managing uncertainty include:

- Managing risk and incorporating tolerances for change in design;
- Considering robust alternatives that perform well under the range of projected conditions;
- Incorporating actionable predictions of future climate and hydrology conditions into the design; or,
- Relying on adaptive management by employing near term strategies that may be adapted when more information on future conditions becomes available.

Even with extensive data, unknowns and uncertainties associated with natural systems and the performance of infrastructure will always exist. Therefore, engineers often use safety factors in design to account for these unknowns resulting in a more conservative design such as a taller, wider bridge, or a wider floodplain delineation. Infrastructure designers may consider multiple design components that work together to achieve a greater safety factor and avoid, for example, simply calling for larger or grouted riprap for bank stabilization. Risk analysis can help in identifying critical components tolerance for change or damage is low along with less critical components where some change is tolerable without project failure.

Robust designs may not be optimal designs under existing conditions; however, a robust design performs well under a wide range of potential future conditions [97]. For example, such a design might consider best available science that suggests there will be more frequent and higher magnitude flood events in the future. Cost-benefit analyses that incorporate a range of future conditions might favor a different design alternative than one that only considers present and past conditions.

Flood frequency estimates may be adjusted based on observed increases in flood frequency and magnitude [98, 99]. Under a scenario of non-stationarity, or changing flood frequency and magnitude over time, design flood estimates based on the most recent record may be reasonable for projects with shorter design lives. These design flood estimates may not be as relevant over longer time periods given further changes to floods expected with a changing climate and urbanization. Vogel et al. [24] propose a method for estimating future flood magnitude at a site based on the assumption that a historical trend there continues to some future date encompassing the infrastructure design life, an assumption that may or may not be valid for a particular project.

Downscaled climate model outputs can be used to estimate future extreme precipitation events for an area and those events can be used in hydrologic models to estimate future design flood magnitudes [100]. However, it is important to recognize the large uncertainties associated with every step in this top-down modelling process and how those uncertainties accumulate. Bottom up approaches to incorporating climate change projections into project design provide a method for dealing with this uncertainty. Under a bottom up approach, one first characterizes the climatic conditions that result in project failure (e.g., levee or bridge overtopping) and then compares these to the spread of future projected climate conditions in a probabilistic manner [101].

Where data are scarce or uncertainty is high, an adaptive management approach may be an appropriate way to deal with uncertainty in the design process. Adaptive management involves implementing a project in phases and adapting design as more information becomes available or as the system evolves and responds to elements of the design. Adaptive management can also apply to the design and construction of projects or project components that can be easily and inexpensively modified as conditions change. This allows for the design to be adapted and for a greater chance for project success [9]. Adaptive management requires flexibility and dedicated funding over longer time horizons to achieve all project benefits.

D. Disaster Response and Recovery

Large floods can be very destructive to infrastructure and communities along streams. In addition to inundation, fast moving water can transport and deposit large amounts of sediment and debris, erode stream banks, and demolish infrastructure. The stream channel after a large flood may have a different alignment than before the flood. The post-flood location of the channel is often put back into its pre-flood location so that damaged and destroyed infrastructure can be reconstructed. In many instances, leaving the channel in its post-flood location and re-locating infrastructure provides a more resilient solution in the face of future floods and maintains the ecological benefit of the newly created habitat within the active river corridor.

After the flood waters have receded, communities may be wondering what to do next, how they can pay for recovery, and how they can get approvals for funding and construction. Roads and bridges may have to be repaired or rebuilt to allow temporary access. Sewage treatment plants may have to be made operational before municipal water supply is restored. Water for firefighting may have to be restored before electrical power is restored.

Recovery after a large flood may involve numerous logistical challenges and long working days for people trying to restore order. These people will likely need help from engineers and scientists who have experience with stream processes and restoration to make sure their recovery efforts will be cost effective. Incorporating knowledge of stream processes into post-flood recovery efforts will result in integrated stream-infrastructure designs that benefit the stream environment and protect critical infrastructure during future floods. Permitting and funding agencies should make sure that new channel and infrastructure designs are compatible with natural river processes and have the necessary resiliency and redundancy to better survive future floods.
Following a catastrophic flood, large volumes of wood, sediment, debris, and trash can be deposited along stream corridors. Wood is an important part of natural and healthy stream systems and can help slow down floodwaters by dissipating flow energy. Large wood that poses little risk to infrastructure is best left in place, thereby saving time and money for more critical work at other locations.

Problems and effective solutions are often unique to specific river locations. In order to achieve cost effective and sustainable solutions, permitting and funding agencies should try to be flexible where possible and avoid rigid “one-size fits all” rules associated with post-disaster recovery.

IV. Summary and Conclusions

This document offers information to infrastructure managers and designers to better understand the stream environment and methods to better build, manage and decommission infrastructure that is economically, socially, and environmentally sustainable. A systems-based approach has been outlined to address the impacts of channel and floodplain modifications, stream crossing, and streamside infrastructure. A decision tool flowchart is presented to inform best practices for designing and managing riverine infrastructure beginning with establishing goals through project implementation. The decision tool focuses on integrating infrastructure as part of a larger master plan, considering fluvial processes and geomorphology to avoid hazards and failure.

Resilient and long-lasting infrastructure would ideally avoid the more dynamic and unpredictable geomorphic settings such as active floodplains. This approach would have the added benefits of protecting the most valuable ecological areas and the physical and biological processes that occur only in river valleys, and maximizing the benefit of infrastructure investments. When infrastructure is replaced, it should be, to the extent possible, relocated out of ecologically high-value and high-risk settings. Existing infrastructure to be repaired can be made to be more compatible with the stream environment by incorporating design elements that accommodate physical and ecological processes.

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