Executive Summary: Ecological Issues in Floodplains and Riparian Corridors

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As part of the process outlined in Washington's *Statewide Strategy to Recover Salmon: Extinction is Not an Option* the Washington Departments of Fish and Wildlife, Ecology, and Transportation were charged to develop Aquatic Habitat Guidelines employing an integrated approach to marine, freshwater, and riparian habitat protection and restoration. Guidelines will be issued, as funding allows, in a series of manuals addressing many aspects of aquatic and riparian habitat protection and restoration.

This document is one of a series of white papers developed to provide a scientific and technical basis for developing Aquatic Habitat Guidelines. The white papers address the current understanding of impacts of development and land management activities on aquatic habitat, and potential mitigation for these impacts.

The scope of work for each white paper requested a "comprehensive but not exhaustive" review of the peer-reviewed scientific literature, symposia literature, and technical (gray) literature, with an emphasis on the peer-reviewed literature. The reader of this report can therefore expect a broad review of the literature which is current through late 2000. Several of the white papers also contain similar elements including the following sections: overview of the guidelines project, overview of the subject white paper, assessment of the state of knowledge, summary of existing guidance, recommendations for future guidance documents, glossary of technical terms, and bibliography.

This white paper examines and synthesizes the literature pertaining to the current state of knowledge on the physical and biological effects of alluvial river channelization, channel confinement, and various channel and floodplain modifications. It also examines and summarizes literature on the mitigation, rehabilitation and restoration of rivers affected by these human modifications. Data gaps in our current understanding of physical and biological process, the effects of human modifications, and appropriate rehabilitation or restoration techniques are also reviewed.

Databases accessible through the University of Washington library were used as primary information sources. Additional information sources included other library systems, the Internet, and governmental gray literature. The reference section in this document cites all papers used for writing. However, the literature review and topic summary are not comprehensive, as there are many additional informational sources that were beyond this review in scope and detail, or that were not discovered. For the ambitious reader, there is an additional database that includes all references that were found, including those not cited in the text.

The paper begins with an overview of ecological and habitat issues associated with streams and riparian zones in Washington State and the Pacific Northwest. A basic review of the science behind river hydraulics, river morphology and habitat formation is given, as is a review of riparian ecology and its importance in maintaining and forming aquatic habitat. Definitions of stream corridors and channel migration zones given by various authors are reviewed.

The results of the literature review are documented in a synthesis of the ecological and habitat effects of channelization, channel confinement and construction. The vast amount of literature on these subjects prohibited an exhaustive review. The most pertinent information is included by individual topic and in summary tables. Past literature reviews, summary reports and detailed investigations are cited for further reference and detailed information. The physical and morphologic effects of channelization are first reviewed to highlight how habitat templates have been or potentially could be modified. Then, the responses of different groups of organisms (invertebrates, fish, plants, birds, mammals) that are dependent on functional riparian corridors are reviewed. Data gaps in our current knowledge in connecting cause and effects relationships in complex ecological systems are reviewed.

The field of hyporheic ecology has developed and grown over the last three decades. Thus, the functional importance of hyporheic and perirheic zones in alluvial streams is reviewed. However, the effects of human activities on the hyporheic and perirheic zones have only been recently investigated. Our current state of knowledge in regards to human modifications of these ecotones is synthesized from the direct literature on the effects of channel modifications on hyporheic/perirheic processes. Derivations are also made from associated literature on the general effects of channelization and general hyporheic processes in unmodified fluvial systems. Many scientific data gaps exist in the hyporheic/ perirheic literature.

The paper includes a section on habitat protection and mitigation techniques. Alternative management strategies such as passive (vs. active) restoration, streamside vegetation retention or promotion, and modified in-channel vegetation removal are reviewed. Recommendations by various authors on how to minimize impacts during design and construction are also summarized. Preservation of channel morphology, incorporation of vegetation into embankments, and alternative bank protection techniques are major features of this section.

In recent years there has been a societal push to rehabilitate and/or restore streams and rivers degraded by channel modifications. The development of restoration paradigms and strategies has been based on our understanding of natural systems. However, relatively little information has been published on working policies, pilot studies or experiments, restoration designs, implementation methods, and effectiveness monitoring of restoration activities. Furthermore, most projects have been implemented for the mitigation and enhancement of small site-specific sites. The paper ends with a review of large-scale rehabilitation and restoration projects and techniques in the literature.

WHITE PAPER

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Submitted to

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Washington Department of Transportation

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Contents

Tables

Figures

Overview of Aquatic Habitat Guidelines Project

As part of the process outlined in Washington's *Statewide Strategy to Recover Salmon: Extinction is Not an Option* the Washington Departments of Fish and Wildlife, Ecology, and Transportation were charged to develop Aquatic Habitat Guidelines employing an integrated approach to marine, freshwater, and riparian habitat protection and restoration. Guidelines will be issued, as funding allows, in a series of manuals addressing many aspects of aquatic and riparian habitat protection and restoration.

This document is one of a series of white papers developed to provide a scientific and technical basis for developing Aquatic Habitat Guidelines. The white papers address the current understanding of impacts of development and land management activities on aquatic habitat, and potential mitigation for these impacts. The following topics are addressed in the white paper series:

- Over-water structures - marine
- Over-water structures - freshwater
- Over-water structures - treated wood issues
- Water crossings
- Channel design
- Marine and estuarine shoreline modification issues
- Ecological issues in floodplain and riparian corridors
- Dredging - marine
- Dredging and gravel removal - freshwater

Individual white papers will not necessarily result in a corresponding guidance document. Instead, guidance documents, addressing management and technical assistance, may incorporate information from one or more of the white papers. Opportunities to participate in guidelines development through scoping, workshops, and reviewing draft guidance materials will be available to all interested parties.

Principal investigators were selected for specific white paper topics based on their acknowledged expertise. The scope of work for their projects requested a "comprehensive but not exhaustive" review of the peer-reviewed literature, symposia literature, and technical (gray) literature, with an emphasis on the peer-reviewed literature. Readers of this report can therefore expect a broad review of the literature, which is current through late 2000. The coverage will vary among papers depending on research conducted on the subject and reported in the scientific and technical literature. Analysis of project specific monitoring, mitigation studies, and similar efforts are beyond the scope of this program.

Each white paper includes some or all of these elements: overview of the Aquatic Habitat Guidelines program, overview of the subject white paper, assessment of the state of the knowledge, summary of existing guidance, recommendations for future guidelines, glossary of technical terms, and bibliography.

The overarching goal of the Aquatic Habitat Guidelines program is to protect and promote fully functioning fish and wildlife habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems. These aquatic and riparian habitats include, but are not limited to rearing, spawning, refuge, feeding, and migration habitat elements for fish and wildlife.

Assessment of the State of Knowledge

Methods

Databases accessible through the University of Washington library were used to locate relevant references for this document. Abstracts were downloaded and reviewed and then the most relevant papers were located, copied, read and synthesized. Additional references were located through the citations in selected papers and from recommendations from other researchers. The reference section in the document contains all papers cited in the text. There is an additional database that includes all potentially relevant references that were found, including those not used in the text. This information is in Appendix A.

Overview of Ecological and Habitat Issues

Basic Hydrology and Hydraulics

An understanding of how water flows is important for understanding how activities in the channel and floodplain affect flow. The amount of water passing a point on the stream channel during a given time is a function of velocity and cross-sectional area of the flowing water.

$$Q = AV \tag{1}$$

where Q is stream discharge (volume/time), A is cross-sectional area, and V is flow velocity. Equation 1 is a form of a mass-balance equation typically referred to by hydrologists as the Continuity Equation.

If you confine the channel through various channelization activities, then the cross-sectional area decreases. If the channel must still carry the same flow or discharge (Q), then equation 1 shows that the flow velocity must increase. An increase in velocity results in an increase in the energy in the flow. This means that the flow can do more work, such as erosion and transport of sediments.

Velocity is a function of channel slope, channel roughness and area. Manning's equation (Equation 2) is commonly used in the United States to study velocity.

$$V = b/n\,(R^{2/3}S^{1/2}) \tag{2}$$

Where V is flow velocity, n is Manning's roughness parameter, b is a coefficient that changes depending on whether one works with metric (b=1) or English units (b=1.49), R is hydraulic radius (cross-sectional area/wetted perimeter), and S is water slope. Wetted perimeter is the length of a line, perpendicular to the direction of flow, across the channel where the stream water is in contact with the bed and the banks.

Evaluation of equation 2 shows that if you decrease the channel roughness or increase the channel slope, velocity increases. As mentioned above, an increase in velocity increases the energy of the flow and the amount of work that the water can do. This can lead to erosion of the channel bed and banks and transport of sediment downstream. Changes in Manning's 'n', the roughness coefficient, are linearly related to velocity. In other words, if 'n' changes by 30%, velocity changes by 30%. Channel roughness is affected by substrate size, vegetation and large wood.

Basic Geomorphology

Schumm (1985) defines three major categories of stream channels: bedrock, semi-controlled, and alluvial. Bedrock channels are stable over time and do not change their position unless there are weak sections of bedrock that allow the channel to shift laterally. Semi-controlled channels have local controls that resist channel movement. Local controls can be areas of bedrock, resistant alluvium, or large wood and logjams (Abbe 2000). In areas without local controls, the channel is subject to migration. By definition, alluvial channels have substrates and banks made of material that is transported by the stream. This means that stream discharges can erode, transport, and deposit the material that shapes the channel. Alluvial channels frequently change their positions and exhibit a range of patterns that are characterized by meander and braiding features. The stability of alluvial channels is much higher when islands and bars have mature vegetation (Kondolf and Curry 1984; Hupp and Osterkamp 1996), but in some situations vegetation has only limited influence on stability and channel migration (Burckhardt and Todd 1998). In alluvial channels, lateral shifts may be normal river behavior, but changes in depth and width indicate true channel instability (Schumm 1985).

While anthropogenic channel confinement and channelization can and does occur in bedrock and semi-controlled stream channels, the majority of this paper will focus on issues in lowland alluvial stream channels and floodplains. Nanson and Croke (1992) give a genetic classification of the morphology and functional processes of floodplains in alluvial rivers. Their classification is based on a streams competence and ability to do work. Primary classification variables include shear stress (tractive force on a streambed) and stream power. Gross stream power, Ω, relates to the internal energy of a stream and its ability to do work, and is defined as:

$$\Omega = \gamma QS \qquad (3)$$

where γ is the specific weight of water, Q is the stream discharge, and S is channel slope (Leopold et al. 1964). The classification scheme is divided into three major distinct groups based mainly on stream power, sediment size and valley confinement:

Class A: High-Energy Non-Cohesive Floodplains

Class B: Medium-Energy Non-Cohesive Floodplains

Class C: Low-Energy Cohesive Floodplains

Within this classification are a total of fifteen subgroups that differ according to stream power, sediment dynamics, erosional and depositional processes, landforms, channel planform, and environment. Geomorphic classifications such as these are not cookbooks for channel design, but they are very useful to the planner, manager and scientist in identifying what type of general system and processes they are dealing with before embarking on more detail site-specific investigations.

Basic Riparian Ecology

Riparian areas are lands adjacent to streams and lakes (Hall 1988). The interactions between the land and water create a diverse and productive habitat for plants and animals. The availability of water, moist rich soils and a variety of plants make the area attractive to wildlife, livestock and people. The size of the riparian area and the extent of interaction between the land and the water vary with the size of the stream (Bilby 1988). In small, upland streams with typically small amounts of stream flow, the forest or other adjacent land use, dominates the stream. Living trees provide shade that keeps water temperatures cool. Dead and fallen trees become large woody debris and provide habitat and cover for insects, amphibians and fish and create pools that help control sediment and nutrient transport. With little sunshine reaching the stream, the forest provides food in the form of insects, leaves, needles, twigs and branches for the insects, amphibians and fish that live in the stream (Gregory et al. 1987). In larger, wider streams the forest and the water interact frequently with each other (Bilby 1988). High stream flows can undercut trees, change the flow path of the river, and deposit nutrient rich sediment onto the forest floor. The forest in turn provides shade and wood to the stream. In very large rivers, a large floodplain forest influences channel migration and development of forest islands within the channel migration zone. In these streams, there is usually an extensive area of active exchange of water and nutrients between surface and subsurface water through an area called the hyporheic zone.

Whatever the size of the stream, riparian areas are critical for maintaining the ecological health of the stream. The water quantity and quality in streams reflects the conditions in the watershed including the riparian areas and the upland areas (Naiman et al. 1992). Healthy streams and watersheds provide clean water, fish, wildlife and livestock habitat, and natural flood and sediment control. Trees and shrubs along the stream slow flood waters and provide time for water to soak into the ground, which can reduce flooding in downstream areas. Streamside vegetation can also filter out pollutants before they reach the stream keeping the stream and groundwater clean. Sediments and nutrients that get filtered out in the riparian zone are quickly colonized by new vegetation, which stabilize the sediment and use the nutrients for growth.

Streams and adjacent riparian areas are subject to frequent disturbances. Natural disturbances include fires, floods, pest and disease outbreaks, slope failures and windstorms (Naiman et al. 1992). Natural systems have a patchwork of forests of different ages with a variety of shrub and tree species. No single area along a river provides the best habitat for all species. The patchwork of forest creates a highly diverse landscape that provides many different habitats than can be used by a large number of plant and animal species. This mix of habitats is the key to a healthy riparian system. However, an increase in the number, size or duration of disturbances can overwhelm the system. Human activities, such as mining, grazing, farming, damming and channelization, logging, urbanization and recreation also disturb riparian areas. It is important to understand the historical rate of disturbances for any given riparian system and not to exceed that frequency, size or duration of disturbance.

Riparian areas affect the delivery and routing of sediment (Everest et al. 1987), water (Sullivan et al. 1987) and wood (Bisson et al. 1987) into and through the stream. Management of upland areas can alter the processes that deliver water, wood and sediment to the riparian areas. This means that a watershed view of riparian areas is essential. Changes in the amount and timing of water delivery to streams affect the plants and animals. If water is delivered to the stream at unusual times or in unusually high or low amounts, various plants and animals many not successfully reproduce or grow. Slope failures provide wood and sediment to streams that help create diverse habitat, but an increase in slope failures can overload channels with sediment or scour them clean, both of which create less diverse habitat. A less diverse habitat means fewer species can live in that area.

Large woody debris (LWD) is a critical component for channel complexity. One popular definition of LWD is wood that is 10 cm or about 4 inches in diameter and more than 2 m long. This definition most likely came from a research program in the 1970s that was concerned with decay of organic matter like leaves, twigs and branches. Once branches reached 4 inches, decay was very slow and hence anything over that size was designated as large and not contributing greatly to decay rates. Today, LWD is viewed as providing stability to streams in the form of pool habitat and sediment and nutrient retention. Recent studies (e.g. Abbe 2000; Savery 2000) indicate that 10 cm wood does not provide all of the desired functions in the stream. Especially in large channels, a key piece (large diameter wood with attached root wad) of LWD is usually necessary to form a stable logjam. Protecting riparian areas will allow trees to grow larger and provide large wood to the stream and forest floor naturally over time (Beechie et al. 2000). LWD on the forest floor provides habitat for a variety of insects, amphibians, reptiles and small mammals and birds as well as a surface for seedlings to become established. These nurse-logs help conifer seedlings survive and out-compete shrubs and hardwoods (Beach 1999).

People often underestimate the amount of riparian habitat because they usually visit streams in the dry summer months. Winter rains fill small channels and off-channel habitats that provide critical habitat especially for juvenile fish during high flows. New regulations have been developed that better define riparian areas and protect the forests around them. Riparian areas are heavily used by humans, wildlife, and livestock and are highly productive and diverse. Maintaining healthy, productive and diverse riparian areas is important for clean water, flood control, fish and wildlife habitat, and recreational opportunities.

Definitions of Stream Corridors and Channel Migration Zones

Budd et al. (1987) defined stream corridors as the surface water drainage systems that included the water body and adjacent riparian lands. Due to the many uses of stream corridors, such as aesthetic amenities, fish and wildlife habitat, outfalls for storm sewers, agricultural uses, water supply, and recreation areas (Budd et al. 1987), whenever land development increases, pressures on stream corridors increase. -* Definitions that can be used to unquestionably identify exact undisputed boundaries of stream corridors or riparian areas or channel migration zones are hard to come by. Clear identification of boundaries is difficult because streams and riparian areas are not fixed in time and space. Streams are naturally areas of disturbance and floods, droughts, fires, and landslides can all affect the location of the wetted stream channel and adjacent riparian areas over time (Naiman et al. 1992).

As the importance of riparian areas has been recognized, efforts have been made to identify the extent of these areas. Studies have begun to assess ways to identify buffer widths (e.g. Leavitt 1998; Castelle and Johnson 2000) and channel migration zones (Budd et al. 1987; Perkins 1993; Skidmore et al. 1999). When trying to define a channel migration zone (CMZ) or area within which the stream is expected to move, one first needs to define a time period. The amount of channel migration will vary depending on the time frame of interest.

For various reasons, many authors have decided that 100 years is an appropriate time frame. Most areas already have a Federal Emergency Management Administration (FEMA) defined 100-year floodplain. FEMA defines a floodplain as "an area adjacent to a river, stream, or waterway that may flood. The 100-year floodplain is an area that has a 1% chance of flooding each year." Any community that participates in the Federal Flood Insurance program is required by the local jurisdiction to elevate, flood proof, or otherwise mitigate against 100-year floods if structures exists in the 100-year floodplain. Federal Flood Maps (FIRM Maps) are available in local planning offices, or by calling toll-free1-877-FEMA MAP (http://www.fema.gov/RegX/env_faq.htm#question_5).

Pollack and Kennard (1999) defined the channel migration zone as the area that the stream and/or its side channels could potentially occupy under existing climatic conditions. It frequently approximates the 100-year floodplain, though it also includes lower terraces and hillslopes adjacent to the floodplain where the stream is likely to meander. In contrast, Skidmore et al. (1999) found the Nooksack River, Washington 100-year floodplain to be wider than the geologic channel, historic channel or meander belt width. This is probably due to the presence of a bridge that had confined the channel for many years.

In the February 17 1998 draft proposal of Oregon Forest Practice Rules the National Marine Fisheries Service (NMFS) defined the CMZ (in Pess 1998) as:

> *…the area a stream is expected to occupy in the time period it takes to grow a tree of sufficient size to geomorphically function in the channel. Spatially, this area generally corresponds to the modern flood plain, but can also include river terraces subject to significant bank erosion. An acceptable method for delineating the CMZ at a particular site, involves delineating either the flood-prone area or the approximate 100-year flood plain, whichever is greater. For larger streams, the 100-year flood plain may already be available on U.S. Army Corps of Engineers or county flood hazard maps. A field method for delineating the flood-*

prone area is approximated by Applied Fluvial (sic) [River] Morphology" (Rosgen 1996). The flood-prone area includes the estimated area that would be inundated by stream flows of two times the bank-full depth. The objective of identifying the CMZ is to ensure that the stream has a protective buffer in the future, even if the stream were to move away from its present location.

The US Fish and Wildlife Service (MBTSG cited in USFWS 1998) gave the following description and rationale for channel migration zones for Bull Trout:

The 100-year floodplain was chosen based on the need to fully incorporate the channel migration zone (CMZ) on low gradient alluvial streams. These stream channels provide critical spawning and rearing habitat for bull trout. An additional 150 feet on either side of the 100-year floodplain is required for the following reasons: 1) it encompasses one site-potential tree height at most locations; 2) provides sufficient width to filter most sediment from non-channeled surface runoff from most slope classes; 3) provides some microclimate and shallow groundwater thermal buffering to protect aquatic habitats inside the channel and the channel migration zone; and 4) provides an appropriate margin of error for unanticipated channel movement, hillslope and soil stability, blowdown, wildfire, operator error, disease, and certain other events that may be difficult or impossible to foresee on a site specific basis.

The Tricounty (see reference to URL) effort in Washington states that CMZ do not exist everywhere, but where they do exist they define the CMZ as:

…the area within the lateral extent of likely stream channel movement over a given stream reach due to stream bank destabilization, rapid stream incision, stream bank erosion, and shifts in location of stream channels.

They intend to identify CMZ boundaries for all stream reaches where stream power, soil conditions, and valley-floor widths are sufficient to support significant potential migration. For regulatory purposes, the Tri-county CMZ will be based on available historic records of channel migration, field indicators of the presence of the side channel in the last 100 years, or 100 years of calculated channel migration, whichever is greater, and will generally include those areas that encompass:

The limit of geologic controls, such as hillslope, bedrock outcrop, or abandoned floodplain terrace; the side channels, abandoned channels, and oxbows; and the outside edges of any signs of progressive bank erosion at the outside of meander bends.

The Washington Forest Practices Board (WFPB 2000) defined CMZ as the

area where the active channel of a stream is prone to move and thus results in a potential near-term loss of riparian habitat adjacent to the stream.

The WFPB manual has descriptions and illustrations of CMZs and delineation guidelines, that include CMZs that have been modified by a permanent levee or dike.

Results of Literature Review on Ecological and Habitat Effects of Channelization

Humans have been altering the earth's surface for thousands of years (e.g. Drower 1954; Cole 1976; Brookes 1988). Riparian areas have been especially vulnerable to human activities. These areas are ideal locations for human habitation providing easy access to water for cooking, drinking and irrigating, transportation, waterpower, food and other amenities.

Channel Confinement and Construction

Channelization can be described as the deliberate or unintended alteration of one or more of the interdependent hydraulic variables of a channel including slope, width, depth, sediment roughness or size, or sediment load. Any combination of changes in these attributes may be made in order to meet the engineering objectives of the channelization. To increase flood carrying capacity, channels are typically widened or deepened. To protect infrastructure such as roads or buildings, channels may be straightened which shortens the length of the river and thus increases channel slope. When inadequate consideration is given to the dynamic and unique characteristics of streams, the physical adjustments that occur following channelization may lead to unexpected or adverse consequences. The inevitable adjustments that occur in the channel may lead to extensive and costly maintenance to retain the engineering objectives that lead to the channelization. Numerous case studies have identified changes after specific channelization activities (e.g. Daniels 1960; Emerson 1971; Cederholm and Koski 1977; Piest et al. 1977; Horner and Welch 1982; Rasid et al. 1985).

It is important to note that changes in morphology are not limited to areas where activities have taken place directly in the channel and floodplain. Changes in channels also occur from changes in surrounding land-use. Urbanizing areas or land conversions from forests to other uses can alter hydrologic patterns that affect channel morphology. For example, changes in number and size of peak flows can lead to channel and bed scour (Booth and Jackson 1997).

Deliberate or unintended channelization and channel confinement can result from structures as well as morphologic channel changes. Structures that can initiate channelization include levees, embankments, berms, dikes, revetments, bridges, floodplain fill, roads (road prisms), railroads, training structures (groins, spurs, etc.), bioengineering structures (cribwalls, rootwad/rock mixtures etc.), and concrete walls. While the above structures can all vary in their size, height, longitudinal extent, longevity, ecological impact, cost and restoration potential, they all are similar in that they typically result in an alteration of one or more of the interdependent hydraulic variables mentioned above. Most of this paper will refer to the impacts of channelization and restoration potential in general terms, with the exact impact of specific structures left up to a site-specific analysis and/or reader interpretation unless otherwise stated and cited.

Channelization has immediate and direct effects on stream processes because it involves direct modification of the river channel. Reasons for modifying river channels include flood control, speedier storm water conveyance, drainage of adjacent lands, navigation, bank stabilization, erosion control, and protection of highways (e.g. Emerson 1971; Schneberger and Funk 1971; Herr 1973; Keller 1976; Brookes 1985b; Brookes 1988). Most of the early studies on the effects of channelization concentrated on the physical effects and changes that occurred to the stream channel. Later, biological effects also began to be noted and evaluated. In 1978, a Task Committee of the Hydraulics Division of the American Society of Civil Engineers did a general overview on the environmental effects of various hydraulic structures (Task Committee 1978).

Activities that are typically included under the heading of channelization include widening and deepening of the channel, straightening of the channel, levee construction adjacent to the channel, streambank stabilization and clearing and snagging of living and dead vegetation in and along the river (Nunnally and Keller 1979).

The combined effect of the physical and biological changes that take place following channelization lead to various alterations in biological systems. These changes affect benthic macroinvertebrates, fish, and aquatic/riparian vegetation from algae and macrophytes to riparian shrubs and trees, as well as terrestrial animals such as amphibians, reptiles, birds and mammals.

Geomorphic analysis (e.g. Lane 1955; Hey 1974; Nunnally 1978; Montgomery and Buffington 1993) has shown than changes in stream discharge, sediment discharge, sediment material and valley slope lead to adjustments or changes in channel width, depth, slope, stream velocity and planform. Brookes (1988) did an extensive review of physical, biological and downstream consequences of channelization activities. Much of the following material is taken from the Brookes review. We have also included information taken from the post 1988 literature that updates Brookes.

The ecological effects of channelization consist of both physical and biological effects to the aquatic system. A typical sequence of events is that channelization leads to immediate changes in physical aspects of the channel. These physical changes lead to longer-term biotic responses that extend over space and time (Simpson et al. 1982). The availability of studies on specific physical effects of specific types of channelization is much higher than corresponding studies on biological effects. The biological effects may be in response to the physical changes in depth, shade, sediment, temperature, altered hydrology, isolation of floodplain habitats, etc. or they may be in response to changes in nutrient cycling and changes in populations of various trophic levels that get transmitted throughout the biological system (Figure 1).

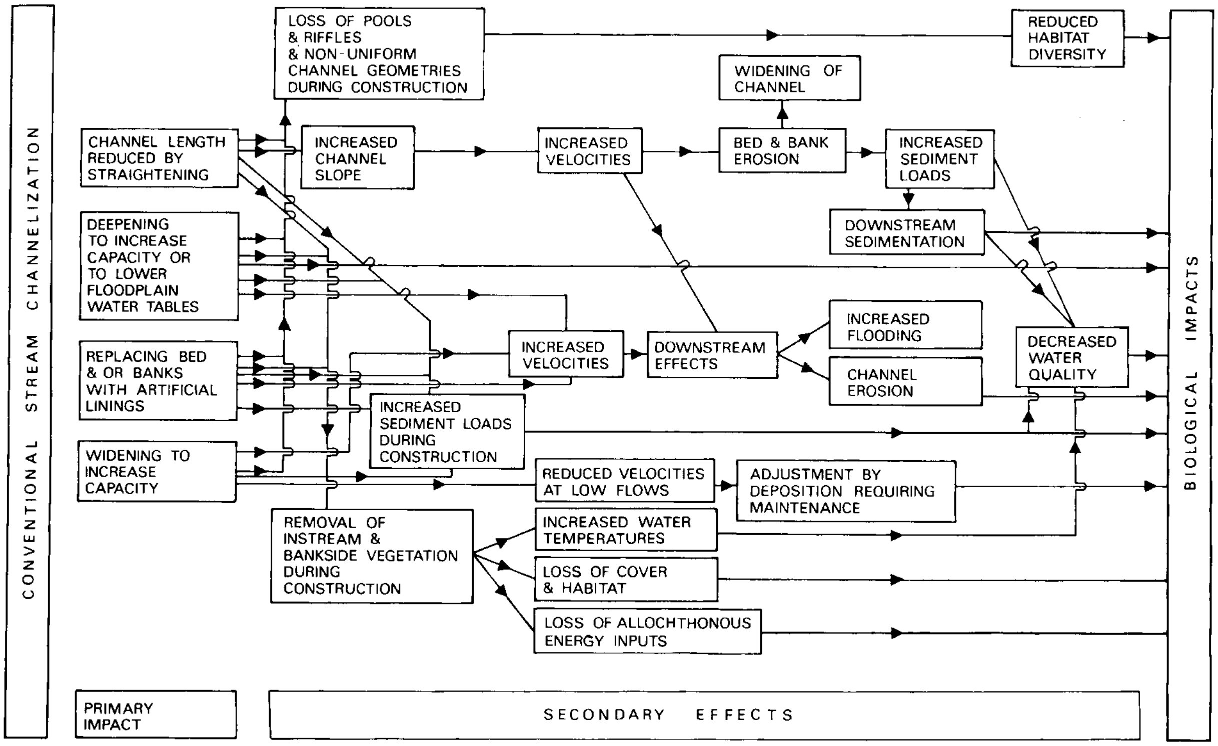


Figure 1. Principal effects of major types of channelization (taken from Brookes 1988)

Physical Effects of Channel Straightening

The effects of shortening a channel by straightening the channel are summarized in Table 1. The type and extent of adjustments will depend on the particular geomorphologic and hydrologic setting of the stream. For example, confined bedrock channels will exhibit a smaller range of adjustments than unconfined alluvial channels.

Table 1. Typical changes in channel attributes following shortening and straightening of the channel (after Brookes 1988)

Local Effects	Upstream Effects	Downstream Effects
Steeper slope	Steeper slope	Deposition of transported sediments
Higher velocity	Higher velocity	Increased flood stage
Increased sediment transport	Increased sediment transport	Loss of channel capacity
Degradation and possible headcutting	Degradation and possible headcutting	
Bank instability	Bank instability	
Channel braiding	Channel braiding	
Tributary degradation	Tributary degradation	

Physical Effects of Levees

Levees are built to artificially increase the flow capacity of a channel. By increasing flow capacity, water that used to spread out over the adjacent floodplain is confined inside the levees. Levees, also known as flood banks, bunds, stop-banks, dikes or earthen embankments, have been used worldwide for centuries. Many large rivers in the United States have extensive levee systems. The Mississippi River system is extensively confined by levees. More than 50% of the Illinois River floodplain, about 50% of the Upper Mississippi River floodplain between navigation reach 19 and the Missouri River, and nearly 100% of the floodplain below the Missouri River confluence is isolated by levees (Theiling 1995).

Construction of levees or embankments is a common engineering solution to flood control. These are traditionally constructed fairly close to the river and need to be higher than natural terraces or banks to contain floodwaters within a narrower area (Hey 1994). Because the flow is confined within the levee walls, the depth and velocity tend to be higher than prior to the construction of the levees. This places higher shear stress on the channel bed and banks, which can lead to greater erosion on site and increased deposition downstream (Hey 1994). Depending on the magnitude of the flow increases within the confined area, many levee systems evolve into bank stabilization projects (Maddock 1976).

If the construction of levees is combined with channel excavation, deposition may occur on site rather than erosion. Griggs (1984) describes a levee/channel excavation project in Santa Cruz California that resulted in increase deposition and significant loss of flood capacity in the altered reach. The channel excavation allowed tidal flows to move much higher into the system that created low velocity water and caused sediment to drop out of suspension.

One method of decreasing the ecological impact of the close levees is the construction of levees some distance from the river. This allows the river to meander within the boundaries created by the levees. The ecological benefits of these ‘set-back’ levees will depend on the criteria used to locate them. Depending on the type and frequency of maintenance within the levees, ecological processes may be more or less intact. Extensive maintenance that includes sediment and vegetation removal does little to reestablish natural floodplain processes.

The effects of fill on floodplains are not addressed directly in the literature review. In general, fill has many of the same effects on habitat conditions as levees (Thronson 1979).

Physical Effects of Clearing and Snagging including the Role of Large Woody Debris

Channel morphology is affected by the presence of trees, shrubs, and logjams. There are few controlled studies on the before and after effects of vegetation removal from the floodplain or stream channel (Shields and Nunnally 1984), but physical effects can be identified by considering the processes affected by vegetation. Vegetation may provide bank stability through root reinforcement of the soil (Krogstad 1995). This strengthens the soil’s resistance to the erosive force of the streamflow. Millar and Quick (1998) demonstrated that the effect of vegetation on bank stability could be expressed as an increase in critical bank shear stress. They estimated that critical shear stress is about three times higher when trees and shrubs are present compared to just grass covered banks. However, there is some evidence that this effect is limited by root density and depth which varies with species and soil types. Rowntree and Dollar (1999) found that willows provided increase bank stability at flows less than bank-full, but did not appreciably affect long-term shifts in channel position from major floods. Nanson and Hickin (1986) found that outer bank migration in meandering channels was largely a function of river size and grain size in the large sand- and gravel-bed rivers that they studied. Vegetation both in channel and along the floodplain provides roughness, which slows water and removes energy from the water. Shields and Nunnally (1984) describe several studies that show changes of 30% in Manning's' 'n' depending on whether the channel is clean or has lots of vegetation and snags. In-channel vegetation also traps and stores sediment and nutrients.

In 1986, House noted a positive relationship between LWD and the health of salmonids. Many studies followed that continued to describe the importance of LWD to productive streams for salmon and the species they rely upon (e.g. Ralph et al. 1994; Montgomery et al. 1995).

Table 2. Typical Effects of Stream Channelization (Brookes 1988; Simpson et al. 1982)

	Stream Characteristics														
	Geometric						Physical					Chemical			
Major Consequences	Slope	Depth/width	Surface area	Total length	Channel Shape	Substrate/cover	Sediment	Light	Temperature	Velocity	Channel drying	Oxygen / gases	Nutrients	pH	BOD/COD
Stream length reduction	X		X	X	X	X	X			X					
Channel deepening for capacity or drainage		X			X	X	X	X	X	X					
Lining or replacing bed and banks		X		X	X	X	X			X		X			
In-stream vegetation/snag removal	X	X	X	X	X	X		X		X		X	X	X	X
Riparian vegetation/snag removal	X					X		X	X		X	X	X	X	X
Increased gradient and velocity	X	X		X	X		X			X	X				

LWD loading is an important factor in pool formation in response reaches (Montgomery and Buffington 1993) and pool abundance correlates with overall salmon habitat quality. Sedell et al. (1985) estimated that salmonid production could be increased several times by raising the debris load in streams with limited amounts of LWD.

While organic debris of all sizes is generally recognized as important for maintaining the biotic and abiotic functions of stream channels, LWD is critical (Bilby and Ward 1989; Sedell and Beschta 1991; Maser and Sedell 1994; White 1996). LWD has a major influence on channel form, sediment transport and deposit patterns, and contributes to organic cycling (Bilby and Ward 1991). The number of pools in a channel system is highly correlated with the quantity of LWD (Woodsmith and Buffington 1996). The amount of large wood in most coastal streams is a small fraction of historic levels (Bilby and Ward 1991; Bisson et al. 1997). Efforts are being made to determine ways to develop appropriate wood recruitment conditions (Peterson and Klimas 1996; Beechie et al. 2000) and estimates of appropriate wood loading in streams (Fox forthcoming).

The functions of LWD include the following:

1. Interrupt the streamflow to trap coarse sediment upstream of the LWD to create bars or islands (Abbe and Montgomery 1996)

2. Modify streamflow to create pool structure/habitat downstream of LWD (Cherry and Beschta 1989)

3. Direct high-water flow to support hydraulic routing (Gippel 1995; Gregory and Bisson 1997)

4. Trap and hold small organic materials (leaves, needles, carcasses etc.) (Culp et al. 1996)

5. Provide hydraulic roughness to the stream during high flow conditions (Abbe and Montgomery 1996)

6. Provide visual aesthetics suggesting natural materials (Bisson et al. 1997)

7. Provide habitat and perches for aquatic and terrestrial invertebrates, amphibians, reptiles, birds and riparian mammals (Borchardt 1993)

8. Provide structure and nutrients for microbiological organisms important to the aquatic ecosystem (Bilby and Ward 1989)

9. Provide habitat for aquatic and semi-aquatic plant communities by providing a stable substrate and silt traps within the structure (Maser and Sedell 1994)

10. Provide cover and shade for juvenile and adult salmon (Bisson et al. 1987) and presumably other fish species

Hydraulic Questions

The hydraulics of native and engineered LWD is not fully understood. In some jurisdictions all stream improvement designs must be assessed to determine whether they will or will not cause an increase in flood elevation. Gippel et al. (1992; 1996) studied the hydraulics of woody debris in the Thompson River, Victoria, Australia and concluded that re-introduction of LWD into previously cleared streams “is unlikely to result in a large loss of conveyance, or a detectable increase in flooding frequency”.

Abbe and Montgomery (1996) have also combined field studies with theoretical and flume studies to explore the hydraulics of debris jams and logs with root wads. Their interest was to better understand how LWD affected stream geomorphic processes. Abbe (2000) and Drury (2000) present information on hydraulics when using wood in large streams for bank protection.

Ecological Questions

LWD and logjams are reported to have a major influence on the storage of organic matter from leaves, needles and salmon carcasses in a stream system (Bilby and Ward 1991; Culp et al. 1996). It slows the movement of fine organic debris (leaves, needles, organic sediments etc.) through the system (Borchardt 1993; O'Connor 1991). LWD also provides a substrate for microbes and algae that are the food for the grazing guild of macroinvertebrates (Maser and Sedell 1994). O’Connor (1991) indicates that colonization by microbes and algae occurs within two weeks of wood deposition in the stream. Macroinvertebrates in turn are a valuable food source for many species of fish, birds, amphibians and reptiles.

Macroinvertebrates are often sampled as part of biological indices for stream health assessments (MacDonald et al. 1991). Most of these indices use benthic sampling. However, Benke et al. (1985) found that wood surfaces of snag habitat were the most biologically rich habitat in terms of diversity and production per unit of habitat surface area in sandy Southeastern streams. O’Neal (2000) reports similar findings in a study in the Pacific Northwest.

Biological Effects of Channelization

Channels that have been unaffected by human activities retain suitable water temperatures for the organisms that have evolved in that location. There is adequate shading, good cover for fish, minimal temperature variations and abundant organic matter input such as leaves, twigs and wood. Channelized rivers tend to have increased water temperatures, less shading from trees, little cover for fish, greater fluctuations in stream temperature and less organic matter input. Natural channels have diverse habitats with varying water velocities as the morphology changes between riffles and pools. The sediment on the channel bottom is sorted and provides many microhabitats for organisms. In contrast, straightened channels tend to consist mostly of riffles and have unsorted gravels that limit the types of habitat available. The diverse nature of natural channels provides slow water refugia during high flow and many resting areas. With less structural diversity, channelized systems have minimal resting areas and organisms are easily swept away during high flows. In low flow periods, natural channels have sufficient water depth to support fish and aquatic species during the dry season. On the other hand, channelized systems may have insufficient depth to sustain required temperatures and dissolved oxygen to sustain life (Brookes 1988).

The species and roles of the organisms occupying the stream change depending on where they occur the ‘continuum’ of the system from headwater creek to large alluvial floodplain river (Vannote et al. 1980; Neuhold 1981). The interaction between the stream and the riparian corridor are greatly influenced by the size of the stream. In the Pacific Northwest, many small streams are located in steep watersheds that limit the development of riparian areas. Large streams and rivers usually occupy flatter, gentler terrain where there is a large potential for an extensive zone of influence between the river and the floodplain (Bilby 1988).

Many of the biological effects that occur as a result of channelization activities are in response to changes in the physical environment. Streamflow, stream velocity, channel morphology, vegetation and channel substrate are all affected by channel activities. The physical nature of stream channels reflects a continuous readjustment of the interrelated variables of discharge, slope, channel width and depth, flow velocity, channel roughness and sediment characteristics (Brookes 1988).

These parameters form the habitat that plants and animals need. Typically, changes due to human activities in the channel migration zone result in a reduction in habitat diversity, which affects the numbers and kinds of animals that can be sustained (Schneberger and Funk 1971; Hahn 1982; Simpson et al. 1982). As the physical habitat changes, stresses are placed on individual plants and animals. These stresses, depending on the tolerance of the species and individual, may limit growth, abundance, reproduction and survival (Lynch et al. 1977). Biologically important parameters that change following channel activities include water temperature, turbidity, flow velocity, variable water depths, hydrologic regime, a decrease or change in vegetation, changes in storage of organic matter and sediment, and changes in the size and stability of channel substrate (Hahn 1982). These changes can decrease habitat connectivity and the exchange of energy and matter between habitats. The direction of change varies by site and circumstance. Because of the complex changes in physical, chemical and biologic properties that follow from channelization activities, it is not feasible to address the biological effects as they relate to individual physical changes. One needs to look at the whole system to understand the changes in the biology.

Requirements and Responses of Aquatic Invertebrates

The conditions in channelized systems discussed above affect the occurrence and distribution of benthic invertebrates. Velocity is one of the critical variables that controls the presence and number of species (Scott 1958; Gore 1978; Milner et al. 1981). Many invertebrates depend on certain velocity ranges for either feeding or breathing (Brookes 1988). The crevices that exist between and under stones create a low turbulence habitat that is favored by mayfly nymphs. Riffles typically have a greater diversity of macroinvertebrates such as mayflies, caddis flies, stoneflies and black flies than do pools. Areas where the stream bottom is unstable or very fine-grained contain few macroinvertebrates. Typical invertebrates in fine sediments are burrowing worms or mayflies (Brookes 1988).

In general, streams with more complex substrates and velocities contain a more diverse invertebrate population (Hynes 1968; Karr 1997). Recent work (O'Neal 2000) has shown wood may provide an equal or even better habitat compared to cobble and gravels. Studies in England have shown that vegetation contributes to invertebrate habitat (Percival and Whitehead 1929; Wright et al. 1983).

Channelization activities tend to disrupt invertebrate communities (Wene and Wicliff 1940; Haynes and Makarewi 1982). Morris et al. (1968) reported a reduction of benthic area of almost 70% and a decrease in standing crop of macroinvertebrate drift of 88% fifteen years after channelization and dredging that eliminated brush piles and pools. Hansen (1971) found a decrease in macroinvertebrates but an increase in drift organisms following dredging of original substrate that provided attachment areas. Realignment of a channel that changed the substrate and reduced pools and shading led to a 75% decrease in invertebrate biomass per unit area (Moyle 1976). Schmal (1978) noted seasonal effects on invertebrate populations with an increased instability of substrate following dredging. Stoneflies were eliminated and the new vegetation and silty substrate favored snails and midges. If substrate changes are avoided following channelization, the recovery of invertebrates may be rapid (e.g. Crisp and Gledhill 1970; Duvel et al. 1976; Hortle and Lake 1982).

The removal of vegetation, wood and snags from channels decreases the ability of the channel to store organic matter that provides food and habitat for organisms (Bilby and Likens 1980). The effects of regular maintenance that includes weed cutting and vegetation removal are variable. In some cases, invertebrate abundance increase and in others it decreases. The effects of this activity on species are probably related to the timing of the activity and whether the substrate is disturbed (Brookes 1988).

Requirements and Response of Fish

Brice (1981) indicates that effects on fish can be immediately apparent following channelization activities even though some of the morphological changes may take some time to adjust. The effects are varied and depend upon the type of work done, the intensity and extent of the work and the extent of morphological change (Brookes 1988). The major habitat requirements of fish are barrier-free migration, suitable substrate, water quality and habitat connectivity for spawning, incubation and rearing, food availability, and shelter from extreme flows and predators (Brookes 1988). Habitat isolation (losses of side channels and/or wetlands) that may occur following channel confinement can strand fish in isolated ponds without connection to the mainstem after high water or prevent access to low velocity refuge.

The natural processes that create and sustain suitable habitat for fishes are often altered by channelization and activities over the entire watershed. The negative effects of fine sediment on the reproductive success of salmonids have been known since 1923 (Harrison 1923). Many of the subsequent studies have been done in the laboratory in order to avoid the variability and complexity in natural streams (Everest et al. 1987). Species, stock, life history pattern, competition, habitat availability, stream gradient, channel morphology, flow regime, basin lithology and historical and current land use across the watershed all interact to determine the effect of fine sediment on fish (Everest et al. 1987). In general, fine sediment has the potential to negatively affect the successful incubation of eggs through limiting gas and fluid flows through the redd, prolonging incubation time due to low oxygen levels, and/or preventing emergence from the redd by fry. Everest et al. (1987) provide a good review of the literature on salmonids and fine sediment. To the extent that channelization leads to increases in fine sediment transport and downstream deposition, one can expect salmonids to be affected. If salmon populations are large enough, there is some cleaning of the gravels of fine sediment that occurs during spawning (e.g. Burner 1951; Cordone and Kelley 1961). Evolutionarily, this may be effective in natural streams with historic numbers of salmon, but is unlikely to have the same success in altered streams with depressed salmon runs.

Most salmonids exhibit light avoidance behaviors (Brookes 1988). Therefore, the removal of vegetation that decreases cover can limit the availability of preferred habitat for salmonids. To the extent that the removal of in-stream and streambank vegetation also reduces shading, water temperatures can be expected to increase. Changes in temperature can alter the rate of egg development, growth rates and rearing success, species competition, and community composition (Beschta et al. 1987).

The effects on fish of channel maintenance in the form of weed cutting have not been extensively studied. Weed cutting may affect feeding and reproductive behaviors. Anything that affects the food web that the fish depend on will affect fish. One reason the literature is lacking on this subject is that the natural variability in fish populations makes it very difficult to separate changes in population that are natural variability and changes that are due to a specific channelization activity. (Brookes 1988).

Requirements and Response of Plants

There are three zones of plant communities in the stream corridor: submerged species in the channel, emergent species along the margins of the river, and species that grow on the banks and terraces adjacent to the river (Peltier and Welch 1969; Haslam 1978). Riparian and aquatic plants provide food, shelter, shade, and organic leaf litter to the stream corridor organisms (Brookes 1988). Aquatic plants are physically impacted or destroyed by dredging and cutting. If changes in the substrate and/or depth occur following channelization, then submerged and emergent species composition is likely to change. The effects of cutting on species depend on the life history of the individual species and time of the cut. (Brookes 1988). In England, Wade and Edwards (1980), have documented major changes in the plants in drainage channels due to dredging and herbicides. From 1840-1976, about 55 of the 100 species known to have occurred are still present. Six species have disappeared, eleven species have recently appeared and others have had notable changes in distribution.

Hill (1976) observed that bank-side vegetation is typically removed for 10-15 meters on each side of the channel for channelization activities and in some places removal extended for 100 m. If upland land use changes follow channelization, there can be widespread destruction of natural plant communities. Typical changes involve altered surface and soil water levels and timing of flows (Brookes 1988). Changes in hydrologic regime, especially in floodplain inundation or lowering of water tables can also affect reproduction of riparian vegetation (e.g. Braatne et al. 1996).

Ferrari (1993) surveyed upland (clear-cuts, young and mature forests) and riparian areas (cobble bars, riparian shrub patches, riparian forests and alder flats) in the Hoh and Dungeness watersheds on the Olympic Peninsula for exotic plant species. Fifty-two exotic plant species were identified and exotics were over 30% more frequent in riparian areas than in upland areas. Young riparian areas had the highest richness, mean number, and cover of exotic plant species of any of the studied environments. The disturbance patterns in riparian areas facilitate the movement of exotics up and downstream.

Requirements and Response of Birds

Riparian areas cover less than 1% of the western United States but the vegetation in these areas provides habitat for more breeding bird species than any other vegetation type (Knopf and Samson 1988). Changes in the composition of riparian vegetation can be expected to have an impact on bird populations.

Not many studies have been done that address the effects of channelization on birds (Brookes 1988). Various studies in the U.S. have shown the importance of riparian habitat for birds (Bottorf 1974; Carothers and Johnson 1975; Henke and Stone 1978; Knopf 1985). Riparian areas provide the juxtaposition of habitat requirements (food, cover, water), and many niches due to the complexity, age range, number of species and structure of the vegetation (Knight 1988). This juxtaposition is created by the disturbance elements common in riparian systems that create a mosaic of habitat patches that provides core habitat (Greco 1999). The disappearance of wetlands and ponds due to floodplain isolation or fill would decrease available habitat for waterfowl.

Questions remain as to the effect on bird populations of riparian buffers compared to intact riparian areas that blend into the uplands (Hanowski et al. 2000). Current evidence, mostly from studies of forest stream buffers (e.g. Yahner and Scott 1988; Small and Hunter 1988; Robinson et al. 1995; Donovan et al. 1997) suggests that buffers need to be between 100-200 m wide in order to limit negative population effects such as nest predation due to edge effects (Hanowski et al. 2000). This assumes that forest birds will use buffers and that bird use is correlated with buffer width, neither of which has been shown (Miklejohn and Hughes 1999; Whitaker and Montevecchi 1999). A study on the effects of riparian areas around small streams (Carey 1988) indicated no discernible effect of bird diversity by the riparian stand.

Requirements and Response of Mammals

Riparian habitats provide large mammals (e.g. opossum, beaver, fox, mink, otter, elk, and deer) with an abundance of prey and carrion, a productive and varied plant community, reduced winter snow accumulation, early spring green-up, aquatic habitat and transportation corridors (Raedeke et al. 1988). Riparian habitat along smaller headwater streams is usually insufficient to support large mammals. Lowland riparian areas along large rivers used to provide productive wildlife habitat, but has been highly modified by humans. Aquatic species such as otter, beaver, nutria, muskrat and mink are most affected by changes in size and composition of riparian areas (Raedeke 1988). Recent studies (O’Connell et al. 2000) have shown that small mammal population numbers are not adversely affected by current riparian buffer sizes, at least in the short term.

Many studies have noted the interaction that used to exist between beavers and riparian areas and streams prior to the almost total elimination of beaver in many locations. Beaver can have a significant effect on streams and riparian habitat (Naiman et al. 1986 & 1988; Gurnell 1998) Beaver ponds and associated wetlands provide good fish and bird habitat (e.g. Bisson et al. 1987; Brown et al. 1996; McCall et al. 1996). Changes in hydrologic regime can likewise affect beaver populations. Streams with altered hydrologic regimes that resulted in higher and more frequent peak flows would affect dam building and stability.

Off-site Consequences of Channelization

Connectivity longitudinally (up and downstream), laterally (floodplain and uplands) and vertically (groundwater, hyporheic, and phreatic) is a major feature of stream corridors (Stanford and Ward 1992). The temporal nature of the system adds a fourth dimension (Ward 1989). These linkages mean that the effects of channelization can be transmitted over areas far beyond the actual work zone. Impacts include changes in hydrology, biology, morphology and water quality (Brookes 1988).

Lateral connectivity is altered by channelization activities including levees, dredging and filling, channel lining, and bank stabilization. The cessation of overbank flooding and the flood-pulse (Junk et al. 1989) effect is suspected to decrease floodplain productivity and biodiversity (Bayley 1995).

Longitudinally connectivity is most clearly affected by dams and diversion structures that either store or remove water, sediment and nutrients from the river (Ward and Stanford 1989). Dams and diversions can have a significant effect on the quantity and timing of flow in the river, water temperature and sediment and nutrient loads (e.g. Lillehammer and Saltveit (1984); Ligon et al. 1995; and the journal Regulated Rivers). The biological and physical effects of dams on streams, channels and floodplains are not discussed in this white paper.

Many observations indicate that downstream flooding is a common, but not inevitable response to channelization actions such as building levees or stream straightening. If the channelization decouples the timing of peak flows merging at confluences, downstream flooding may be decreased. Draining and filling of wetlands and swamps in floodplains reduces the storage capacity of the system and leads to more downstream flooding (Brookes 1988).

On-site effects of channelization typically increase the channel slope and water velocity. As a result, there is more erosion and transport of sediment downstream where it is deposited in areas that have not had the transport capacity of the stream altered. Morphologically, this leads to incision or widening of the channel on-site and aggradation or filling of the channel downstream when the sediment is deposited.

Water quality effects are highly site specific and are controlled by the watershed land use, extent of channelization and the length of recovery period (Brookes 1988). Shields and Sanders (1986) reviewed studies on the effects of excavation and diversion on water quality. Observed water quality changes were due to increased sediment inputs and decreased shade. Most of the measured water quality parameters increased by 50-100% during construction compared to pre-construction values. Little (1973) reported that during and after channelization, large amounts of suspended sediments are typically released and deposited downstream where they adversely affect aquatic life. If the channelized reach is very long, temperature increases due to the reduction of shade may persist downstream (Duvel et al. 1976). Few studies have directly addressed the effects of channelization on water quality components such as oxygen, nutrients and ions (Brookes 1988).

Biological effects of changes in hydrology, morphology, or water quality would be the same as discussed earlier and the downstream extent of these effects would be highly site specific.

Effects of Specific Structures

There are some studies that have looked at the biological effect of specific structures and bank stabilization techniques, such as riprap, spur dikes, and revetments. Hjorte et al. (1984) looked at fish and invertebrates along revetments and natural channel areas of the Willamette, River, Oregon. Hjorte et al. (1984) found different numbers and species of fish and invertebrates in natural stream areas compared to riprap banks. Fewer fish species used riprap areas in high densities than used natural areas. Fish found in revetment areas tended be ones that fed on algae or diatoms growing on the stones or fed on bottom dwelling invertebrates. Invertebrates found in the revetments were species that preferred a very stable bottom and either clung to the stones or hid in crevices. More fish species were found in areas with natural banks due to the greater diversity of habitat in these areas.

Li et al. (1984) compared larval, juvenile and adult fish use of natural and channelized habitats in the Willamette River, Oregon. They concluded that continuous revetments are not good larval fish habitat. The combination of proximity to fast water, steep bank slopes, greater water depth, and cooler temperatures does not provide suitable habitat for larval fish. Spur dikes have a greater diversity of habitats than continuous revetments and appear to be intermediate in habitat quality between natural banks and continuous revetments. Low-angle beaches that develop between spur dikes can provide good larval fish habitat. Natural banks have the greatest diversity of habitats within secondary channels, fast and slack water areas and backwaters and, as expected, have the most diverse fish species composition.

Peters et al. (1998) looked at seasonal fish densities in Washington at sites with various bank stabilization structures. They conducted a survey of typical bank stabilization methods and found that 496 of 667 projects used riprap or riprap with deflectors. Only 29 projects used bioengineering or large woody debris. Of all project types (riprap, riprap with large woody debris, rock deflectors, rock deflectors with large woody debris and large woody debris) surveyed by Peters et al. (1998), only sites stabilized with large woody debris consistently had higher fish densities in spring, summer and winter than the control sites without any stabilization structures. Riprap sites consistently had lower densities than control sites. At all sites, fish densities were generally positively correlated with increasing surface of large woody debris and increasing amounts of overhead riparian cover with 30 cm of the water surface.

Discussion/Data Gaps

One of the biggest gaps in the literature is information that directly relates habitat changes to fish productivity (Brookes 1988). This information is very hard to collect, especially for anadromous fish, because many factors affect their overall productivity and survival besides freshwater habitat.

Another major problem is the general lack of adequate (or any) pre- and post-construction or monitoring of restoration activities. There is almost never any information collected for any substantial period of time preceding channel activities. Funding for monitoring to follow-up on physical and biological responses to channel activities is seldom available.

In general, there is very limited information available on amphibians and reptiles that is directly related to channelization and floodplain changes. Bury and Corn (1987) discuss amphibian responses to timber harvest but not in the context of channelization.

Hydrogeomorphic and Ecological Effects of Channel Confinement and Channelization on the Hyporheic and Perirheic Zones

Introduction to the Hyporheic and Perirheic Zones

While hydrologists have long known about the dynamic nature of surface water/groundwater interactions along river systems, studies of these exchanges during the last two decades by ecologists and hydrologists has uncovered the functional importance of the hyporheic zone to the physical, chemical and biological integrity of fluvial ecosystems (Boulton et. al. 1998). Traditionally, water along river systems has been defined as either surface water or ground water. However, other bodies or zones of water have recently been defined that are ecotones or intermediate in nature (physically, chemically and biologically) to surface and ground water. Hyporheic zone is a broad term that defines the “saturated interstitial areas beneath the stream bed and into stream banks that contain some proportion of channel water or that have been altered by channel water infiltration (advection)” (White 1993). This physiochemical definition relies on the presence of some proportion of surface water in the interstitial areas surrounding rivers [usually 10%, (Triska et al. 1989a)] and is the preferred definition of the hyporheic zone for most biogeochemical studies (Edwards 1998). However, Brunke and Gonser (1997) argue that an exact definition of the hyporheic zone does not contribute to its functional understanding as a complex ecotone of complex gradients and non-static boundaries over time and space.

Because of the complexity of the hyporheic zone, individual researchers studying specific systems and asking specific scientific questions can define the system to meet their objectives.

Many ecologists have defined the hyporheic zone as the area where hyporheic fauna (hyporheos) occur, which changes according to time, space, faunal composition and geographic location (Edwards 1998). Other researchers have further divided the hyporheic zone into distinct subzones or biotypes according to physical, chemical and biological characteristics. Boulton et al. (1992) divided the hyporheic zone into three subzones or types: the wetted channel or shallow hyporheic zone, the floodplain hyporheic zone and the parafluvial hyporheic zone. The wetted channel hyporheic zone is the shallow subsurface water zone directly beneath the wetted channel in close contact with biological and hydrological processes in the river channel. The floodplain hyporheic zone is located outside the bank-full channel in lowland floodplain river systems and is above the true groundwater zone of an unconfined aquifer up to the height of the floodplain water table. The parafluvial hyporheic zone is the zone of hyporheic water beneath the dry sediment bars within the active channel boundaries (Edwards 1998). While these subzones might appear distinct, they are all interconnected ecotones of a mixture of surface and ground water (see Figure 2).

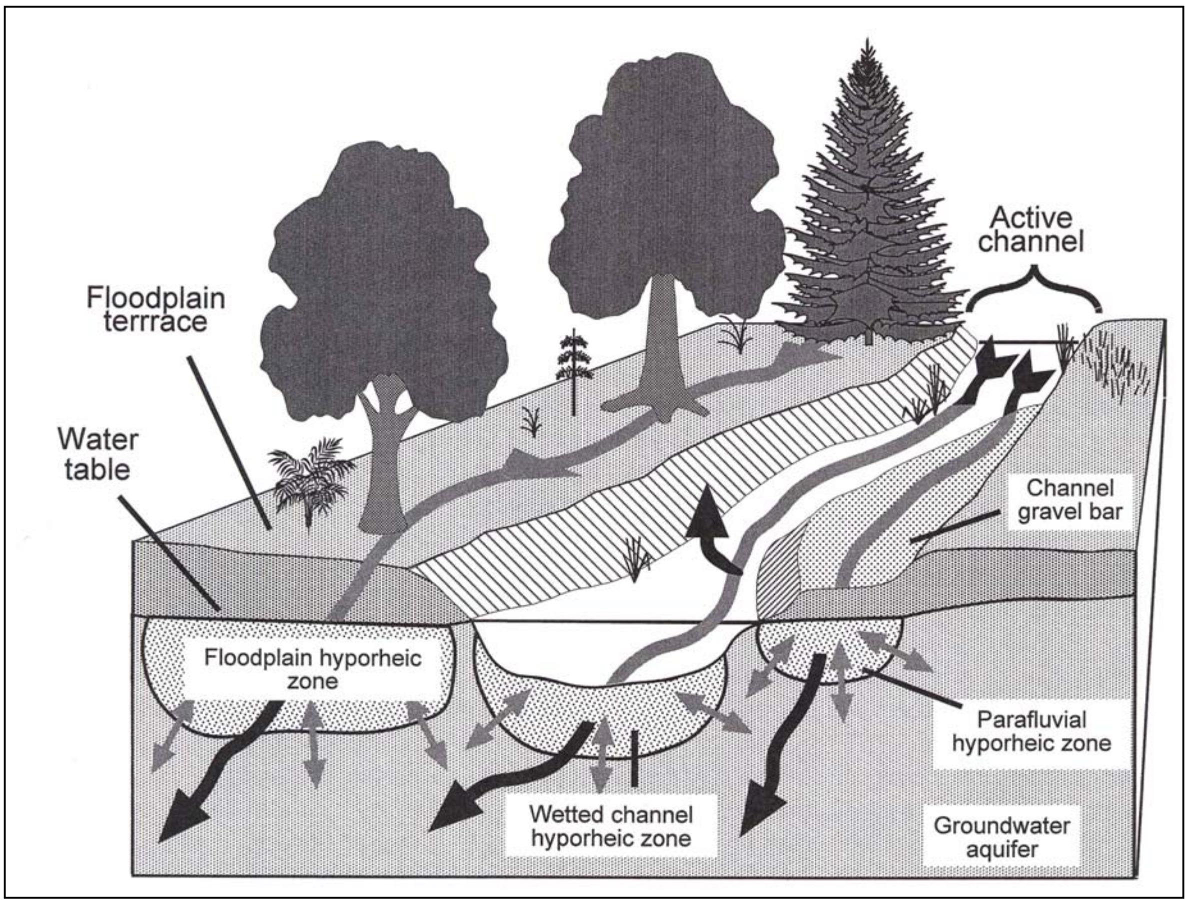


Figure 2. Hyporheic zones (from Edwards 1998)

A more hydrologically complicated view of floodplain hyporheic zones, gradients of mixing water of different chemistry, and biological and physical origin is given by Mertes (1997). She defines the ecotone of mixing floodplain surface waters as the perirheic zone. From her study of numerous large river systems around the world at different stages of human disturbance, she found that floodplains are complex mixing zones of water from numerous sources: groundwater, hyporheic water, local tributary inputs, hillslope runoff, direct precipitation, and antecedent soil and surface water from prior floods (e.g. ponding).

Research by Mertes (1997) also sheds light on the relative importance and presence of the perirheic and hyporheic zones in relation to the spatial and temporal changes in substrate size, porosity and hydraulic conductivity along longitudinal river corridors. She predicts that fine alluvial floodplains will limit the development and extent of a hyporheic zone and accentuate the development of a perirheic zone through reduced subsurface flow rates and increased surface ponding. Thus hyporheic zone development is predicted to be least in headwater streams with little alluvium, to peak in intermediate reaches dominated by cobble, gravel and coarse sand, and then decline again in extreme lowland rivers systems dominated by fine alluvium (Boulton et. al. 1998).

As stated above, the dimensions of the hyporheic zone can vary dramatically depending on the stream size, stream discharge, sediment porosity and volume, and vertical and lateral exchange rates. In small headwater streams, the hyporheic zone is typically on the order of several meters both vertically and horizontally or entirely absent due to lack of alluvium or significant exchanges of water (streams dominated by uni-directional groundwater input) (White 1993). In large montane and lowland alluvial valleys, the hyporheic zone typically is on the scale of several meters below the streambed and up to 100-meters wide. In some highly conductive stream systems (e.g. Flathead River, MT; Yakima River, WA; Methow River, WA), the hyporheic zone can extend over 10 meters deep into alluvium and up to 3 km wide across the floodplain (Stanford et al. 1994; Stanford and Ward 1988; Stanford and Ward 1993; Whiting and Sweeney 1999). In some of these larger systems, water and materials can be transported most easily and rapidly through floodplain alluvial aquifers in a complex network of 'paleochannels' (Stanford and Ward 1993). Paleochannels are a result of 'successive elevations [and locations] of the laterally migrating river channel that were buried as the deposition of alluvium built the floodplain' or 'they may have been formed during the intensive outwash period following glacial retreat [in some parts of western North America] and subsequently buried by recent flood events' (Stanford and Ward 1993).

Due to the extremely complex nature of the hyporheic zone and the lack of an all-encompassing definition, the spatial delineation of the hyporheic zone is difficult. There are several common methods of delineation used by ecologist and hydrologists (Edwards 1998). All delineation methods require the installation of wells or piezometers to sample the subsurface water. The most common method involves monitoring the concentrations of naturally occurring solutes or hydraulic characteristics such as pH, electrical conductivity, ion concentration and temperature. Differences in these variables are used to delineate surface, ground or hyporheic water via variable contour plots, which help define the gradational hyporheic zone. Other methods used to delineate the hyporheic zone include:

- The use of conservative tracers or dyes to map the spatial extent and residence time of subsurface waters

- The monitoring of water heights at the stream channel and nearby wells to detect close hydraulic connectivity (Stanford and Ward 1993)

- The mapping of the presence/absence of specific hyporheic fauna pumped from wells, which have specific affinities for surface, ground or hyporheic water

Functional Importance of Hyporheic Zones, Hyporheic Corridors and Perirheic Zones

For the last twenty years, ecologists and hydrologists have been studying the functional processes of the hyporheic zone as they relate to hydrologic exchange processes, nutrient dynamics and biotic lifecycles and habitat. The plethora of literature and research on the above topics, especially nutrient dynamics and hyporheic ecology, prevents a thorough review of this literature. The reader is referred to the cited literature in this paper and the additional references therein for more detailed information on these subjects. However, a brief summary of the functional importance of the hyporheic zone to river corridors and ecological diversity is given. For more information on these topics, see the detailed reviews of the hyporheic zone by Brunke and Gonser (1997), Edwards (1998), Boulton et al. (1998), Stanford and Ward (1993), and Gibert et al. (1997a).

Major Functional Attributes of the Hyporheic Zone

1. Retention and storage of water (Beard 1974; Lajczak 1995; Mertes 1997)

    - Results in longer runoff flow paths due to influent (losing stream) conditions during flood events,

    - Reduces magnitude of peak flows

    - Sustained baseflows (summer effluent conditions)

2. Promotes habitat complexity (Boulton 1998; Brunke and Gonser 1997):

    - Hyporheic sub-zone complexity (wetted channel hyporheic zone, floodplain hyporheic zone, parafluvial hyporheic zone)

    - Lateral and vertical advection creates habitat

        - Streambed roughness promotes flow paths in and out of bank and bed
        - Heterogeneous substrate deposits with variable permeabilities

- ☐ Connected hyporheic corridors (Stanford and Ward 1993)

3. Regulation of stream temperature (Boulton 1997 & 1998; Brunke and Gonser 1997; Baxter and Hauer 2000):

   - ☐ Hyporheic upwelling zones; spring brooks; influent areas

     - – Cooler than surface water in summer (thermal refugia for species like salmonids)
     - – Warmer than surface water in winter (thermal refugia from freezing, as with some species of incubating salmonid embryos)

4. Provides interstitial volume as habitat for hyporheic organisms or *hyporheos* (Williams 1984; Stanford et al. 1994):

   - ☐ Habitat for crustaceans, segmented worms, flatworms, rotifers, water mites, juvenile stages of aquatic insects, bacteria, protozoa, and fish embryos

   - ☐ Hyporheos help maintain their hyporheic habitat by modifying the porosity of the subsurface sediments through feeding and burrowing (Danielopol 1989)

5. Refugia for channel invertebrates and fish eggs and pupae from floods, droughts and water quality disturbances (natural and human induced) (Williams 1984; Stanford et al. 1994):

   - ☐ Insect recolonization after disturbances

   - ☐ Semi-predicable location for the placement of fish and invertebrate embryos

6. Buffering and filtering ecotone between the terrestrial and aquatic environments (Peterjohn and Correll 1984; Brunke and Gonser 1997; Edwards 1998):

   - ☐ Retains and transforms nutrients (nitrogen, phosphorus, Fe, Ca, Mg)

7. Enriches habitats (Boulton 1993; Stanford and Ward 1993; Brunke and Gonser 1997; Edwards 1998):

   - ☐ Hyporheic zones are generally enriched with solutes compared with surface waters

- Chemical and microbial processes occurring in the hyporheic zone can have substantial ramifications for surface biota

- Hyporheic zones retain and transform solutes for biotic production and future release

8. Downwelling (influent) stream water provides (Stanford and Ward 1993; Stanford et al. 1994; Geist and Dauble 1998):

- Dissolved oxygen (DO) and organic matter for hyporheos organism-like microbes, invertebrates, and salmonid embryos

- Spawning sites for certain salmonids (e.g. salmon)

- Substrate at downwelling area promotes the trapping and retention of organic matter in the hyporheic zone

  - Stimulates biofilm growth in downwelling areas
  - Organic decomposition and transformation by bacteria
    Food resources for primary consumers
  - Watershed nutrient retention

- Aquifer recharge

9. Upwelling hyporheic/subsurface water provides (Wallis et al. 1981; Stanford and Ward 1993; Stanford et al. 1994; Brunke and Gonser 1997; Edwards 1998; Baxter and Hauer 2000):

- Nutrient enriched water for stream organisms

  - Source of inorganic nutrients after mineralization in the hyporheic zone
  - Input of phosphorus due to loss of DO, change in redox, and release of phosphorus

- Hyporheic nitrification

  - Accumulation of nitrogen along flow paths
  - Mineralization of organic matter
  - Regeneration of inorganic nitrogen

- Source or sink for Dissolved Organic Carbon (DOC)

- Spawning sites for certain salmonids (e.g. charr)

- ☐ High in-stream productivity in upwelling zones, e.g. Hot Spots
  - – Increased ecological diversity and biological production in otherwise nutrient poor river systems in the Pacific Northwest

10. Release of retained organic material from the hyporheic zone during disturbances (e.g. bed load movement) (Wootton et al. 1996; Brunke and Gonser 1997)

11. Control of biodiversity and ecosystem metabolism (Brunke and Gonser 1997):

    - ☐ Hyporheic residence time can control hyporheic biodiversity and ecosystem metabolism

12. Promotion of diverse and functional riparian communities (Peterjohn and Correll 1984; Gregory et al. 1991; Girel et al. 1997; Steiger et al. 1998)

Major Functional Attributes of the Perirheic Zone

1. Major ecotone between aquatic and terrestrial habitats in lowland floodplain ecosystems (Naiman et al. 1988)

2. Mixing of sediment laden, nutrient rich river water and clear, nutrient poor floodplain water (Mertes 1997)

    - ☐ Promotes high levels of floodplain productivity (periphyton and phytoplankton

3. Important seasonal habitat for riverine organisms (e.g. Salmonids in the PNW) (Andrus et al. 1997; Whitener and Kennedy 1998)

4. Overbank floodplain deposits create geomorphic heterogeneity and landform diversity (Mertes et al. 1995).

    - ☐ Promotes complex, functional vegetation communities

5. Storage areas for water, sediment and nutrients (Mertes et al. 1995)

    - ☐ Reduced peak flow magnitudes

    - ☐ Temporary and permanent sediment storage

Effects of Channel Confinement/Channelization on Hyporheic and Perirheic Zones

Direct research on the effects of various anthropogenic disturbances on the hyporheic zone, perirheic zone and hyporheos are extremely limited. Many of the potential effects of hyporheic zone alteration can be inferred from the general effects of channelization/confinement projects and the functional importance of the hyporheic and perirheic zones, but a huge data gap still exists. A summary of the most relevant existing literature pertaining to the potential effects of hyporheic disturbance will be given followed by an analysis of current data gaps.

In one of the few studies directly addressing the impacts of land use on hyporheic function and ecology, Boulton et al. (1997) compared the hyporheic ecology of five small streams in New Zealand under different land use, native forest, exotic pine forest and pasture. Many distinct abiotic and biotic differences were observed between the different sites. As expected, the temperatures of hyporheic water at the pasture site were significantly higher than either of the two forested sites. This was attributed to the lack of riparian shading and warmer stream temperatures. Warm water temperatures further reduce the levels of dissolved oxygen in the sediments (Allen 1995), which can be a critical control on the presence or absence of certain hyporheic taxa. Boulton et al. (1997) predict that as stream and hyporheic temperatures warm up due to a lack of riparian shading, the hyporheos community structure can dramatically shift towards a community dominated by a few taxa tolerant of low oxygen (hypoxia) and high temperatures.

Boulton et al. (1997) also note the effects of a lack of a riparian canopy on other physical and ecological processes. They found that the forms of particulate organic matter entering the hyporheic zone differed between sites. Native forests contributed diverse types of leaf materials and woody debris to the hyporheic zone while pasturelands only contributed a few species of grass that decomposed rapidly and contributed little to aquatic production. Organic matter contribution from the exotic pine site was in between that of the other two sites, due to its monoculturistic contributions.

As noted in other sections of this white paper, the removal of riparian trees and understory vegetation can dramatically alter the stability of streambanks and hillslopes (Simon and Hupp 1992; Simon 1994; Shields 1991; Shields and Gray 1992; Kondolf and Curry 1986), which can lead to slumping, fine sediment input and unnatural erosion rates. Boulton et al. (1997) note that slumping of hillslopes and streambanks in unvegetated pasture streams leads to the smothering of lateral bars with sediment (especially fines), resulting in narrower channels with reduced volumes of potential hyporheic habitat. Furthermore, in small New Zealand streams, the lack of shading and increased slumping of sediment encouraged the growth of aquatic vegetation and algae. This encroaching vegetation has the potential of trapping fine sediment, which can smother potential hyporheic habitat and allow for the further encroachment of aquatic vegetation.

As related to the potential anthropogenic alterations of the hyporheic zone mentioned above, Boulton et al. (1997) found that pasture streams supported significantly less hyporheos diversity than the native forest. They largely attributed this to high levels of interstitial fine sediment and the reduction of downwelling oxygen-rich surface water which each promote hypoxic conditions intolerable to some organisms. Furthermore, exotic pine forests had similar taxonomic diversity as the pasture stream. Reduced diversity in these streams was attributed to changes in detritus and nutrient dynamics, lack of understory bank-stabilizing vegetation, and historical disturbances.

Another unique research study directly monitored and compared the pre- and post-project impacts of river channelization on the hydrology and hydrogeology of a catchment. Essery and Wilcock (1990 and 1991) documented the effects of channelization (mainly dredging and straightening) on catchment water yields, groundwater levels, and water storage for the River Main in Northern Ireland. The goal of their research was to document the intended drainage and drawdown of the floodplain water table, the expected reduction of overbank flooding, and the expected augmentation of low flows. After intensive monitoring of both control and modified catchments, they concluded that there was insufficient evidence to indicate any significant or sustained regional water table drawdown due to channelization measures. They also found that river channelization had no significant short-term effect on fens and lowland raised bogs far from the river. However, while they did not find any significant water table changes in wells far from the river, they did document significant changes in water table levels in the gravel aquifer adjacent to the river. An increase in low base flows was also detected following channelization, which was attributed to the release of water from the local gravel aquifer. The drawdown effects were limited to a narrow zone (i.e. the hyporheic zone) approximately 100m wide adjacent to the river channel. This research suggests that the short-term effects of channelization on groundwater levels might be insignificant in the regional context, but that dramatic dewatering effects can be seen in local aquifers and hyporheic zones adjacent to the river.

The research cited above indicates a potentially instantaneous and substantial effect that channelization can have on the spatial and temporal extent of the hyporheic zone and the frequency and direction of exchange processes between the channel, the floodplain and local aquifers. By lowering the channel bed elevation, increasing the bank-full channel area, and dramatically reducing the frequency of overbank flooding, channelization schemes can greatly alter the exchange processes between rivers and local aquifers (Essery and Wilcock 1990 & 1991). Channel incision also typically follows channelization projects (Simon and Hupp 1987; Simon 1994; Hupp 1992), which can further degrade the exchange potential between a river and its floodplain and parafluvial hyporheic zones. The balance between local aquifer recharge during high flows and baseflow augmentation from local gravel deposits during low flows can be altered by channelization projects to produce exchange processes dominated by uni-directional flow paths from the local aquifer/hyporheic zone to the river (Galay 1983; Keller and Kondolf 1990; Brunke and Gonser 1997). Essentially, channelization projects have the potential to drain and dewater local aquifers/hyporheic zones adjacent to river systems. Channelization causes the greatest decline in groundwater levels nearest the stream and diminishing declines with increased distance from the stream (Winner and Simmons 1977; Essery and Wilcock 1990 & 1991). The result is the permanent removal of potential saturated storage volume essential for aquatic organism habitat, riparian vegetation [and subsequently bank stabilization (Kondolf and Curry 1986)], temperature regulation and nutrient exchange (Edwards 1998). While water exchange processes can still occur to some extent following channelization, natural hyporheic functions and habitat forming processes will be dramatically altered with still relatively unknown effects on physical exchange processes and aquatic biodiversity.

As stated in the functional importance of hyporheic zones section above, hydrologic exchange processes within the hyporheic zone can significantly control solute and nutrient dynamics within a given watershed. Several studies from the eastern United States document the potential impacts of stream channelization and confinement on nutrient processes (Kuenzler et al. 1977; Winner and Simmons 1977; Yarbro et al. 1984). As cited above, Winner and Simmons (1977) also found that channelization projects significantly lowered groundwater levels adjacent to stream channels. Associated with this drawdown was a significant increase in groundwater recharge to the stream channel. They predicted that dissolved nutrients and solids concentrations would increase following channelization, especially during low flow when local groundwater sources dominated discharge volumes. The potential ecological effects of these changes in solute dynamics on perirheic, hyporheic, riparian, and aquatic diversity were not investigated and are relatively unknown.

In a related study, Yarbro et al. (1984) found that nitrogen and phosphorus exports were significantly higher in channelized streams than in nearby natural watersheds with intact riparian floodplains, wetlands, and water table levels. Many researchers have found that intact floodplains and riparian forests effectively retain nutrients, making them available for perirheic, hyporheic, riparian, and lotic organisms and reduce nutrient exports to downstream river reaches and estuaries (Peterjohn and Correll 1984). This retention occurs via nutrient uptake along subsurface flow paths through the riparian zone or through sediment and nutrient retention and transformation in the perirheic zone of the floodplain (Mertes 1997; Peterjohn and Correll 1984). While the presence or absence of floodplain wetlands, hyporheic zones and active perirheic mixing zones are important in the retention and transformation of nutrients in a watershed, Yarbro et al. (1984) found that the loss of these natural attributes were not solely responsible for alterations in nutrient export. The process of denitrification is also important in the removal of nitrogen in shallow groundwater, hyporheic zones and perirheic zones (ponded floodplain water) with relatively long residence times and saturated conditions where denitrification can take place. Yarbro et al., (1984) hypothesized that the lowering of the groundwater table associated with channelization lead to the creation of aerobic soils and thus greater mineralization rates of organic matter and enhanced soil conditions for nitrification. The increased transport rates of water and nutrients associated with channelization and water table drawdown subsequently promoted the increased export of nutrients, especially nitrogen from channelized watersheds. Yarbro et al. (1984) also found that phosphorus export also increased with channelization. They attributed this to the loss of floodplain connectivity and potential uptake sites in floodplain forest and perirheic zones (soluble reactive phosphorus). In addition, increases in particulate phosphorus were attributed to increased erosion potential along streambanks due to increased velocities associated with channel confinement. Thus, the removal of riparian vegetation and loss of floodplain connectivity only partially explain the complex change in nutrient dynamics associated with channelization, with much of the alterations occurring due to changes in shallow groundwater and hyporheic nutrient dynamics.

Studies like the one above shed more light into the importance of hyporheic, perirheic and shallow groundwater zones to the proper function of fluvial systems. In many natural systems in the Pacific Northwest, the hyporheic zone functions as a source of nutrients for relatively nutrient poor surface waters. However, in degraded fluvial systems in urban and agricultural areas of the Pacific Northwest and elsewhere where anthropogenic nutrient loading can greatly exceed background conditions, the hyporheic zone can act as a sink for nutrients entering the hyporheic zone along many different paths. In many heavily developed watersheds, intact riparian zones, floodplains, perirheic zones and hyporheic zone have the potential to significantly mitigate anthropogenic disturbances such as increased nutrient loading, altered discharge and sediment transport regimes. However, channelization often is associated with human development, masking any potential benefits of a functional riparian corridor, hyporheic corridor and channel migration zone. Therefore, the preservation of intact hyporheic corridors and floodplain connectivity is key to the promotion of functional fluvial systems. In currently degraded areas, the potential for reconnecting floodplain ecosystems and restoring hyporheic zones and corridors exists and is a growing sub-field in river restoration, which will be discussed below.

Due to a lack of hyporheic research in regulated and channelized river systems, the effects of anthropogenic modifications and land use on the hyporheic zone, the hyporheos, and aquatic diversity and production are still relatively unknown and undocumented (Boulton et al. 1997). From the above examples, it is fairly obvious that different types of channelization projects have the potential to dramatically alter the extent and exchange rates of hyporheic zones. From the existing research on the functional significance of the hyporheic zone, many inferences can be drawn regarding the potential effects of modifying and simplifying a fluvial system on the hyporheic zone and its diverse functions. But whether human modifications completely truncate hyporheic functions and processes along a river corridor or whether they are just partially suppressed by anthropogenic constraints is still unknown for most catchments (Ebersole et al. 1997).

The presence of a true hyporheic zone (definition dependent) in highly modified fluvial systems is still subject to question. However, Stanley and Boulton (1993) documented the presence of a diverse hyporheic fauna in the Rhone River, France, which has been subject to intense human modifications for hundreds of years. In a modified arm of the river currently used as an overflow canal, they documented the existence of significant local exchange processes and the presence of distinct hyporheos utilizing different hyporheic microhabitats. Different hyporheos showed strong relationships between migrational patterns and the magnitude and duration of highly modified discharge events through the canal. This research points to the need for additional research on the presence, extent, and function of hyporheic zones in regulated and channelized river systems in order to determine the importance of these modified ecotones, the degree of hyporheic degradation, and the potential for hyporheic zone restoration.

Data Gaps

While the topics and references reviewed above do not represent an exhaustive review of hyporheic process literature or the literature pertaining to the effects of river channelization/confinement on the hyporheic zone, they do highlight most of the major functional attributes of the hyporheic zone and some potential sources of physical and biological degradation causes by anthropogenic engineering projects. The scientific understanding of surface-groundwater interactions is still in its infancy, with the bulk of the research focused on understanding basic physical and biological processes in relatively unmodified environments. Very little hyporheic research has been conducted in highly altered and degraded fluvial systems. As the understanding of these processes becomes more solidified in the scientific community, more attention will undoubtedly be focused toward the effects of land use and other human activities on surface-groundwater ecotones. Thus, many data gaps exist in the current scientific literature pertaining to hyporheic degradation. Below is a partial list of potential research topics pertaining to the effects of channelization, confinement and other human disturbances on the hyporheic zone and its many functions. Some of the topics listed below may have existing literature pertaining to them that were not reviewed or uncovered in this literature review.

1. Direct effects of truncating portions of the physical water habitat of organisms that temporarily or permanently use the hyporheic zones as habitat

2. Ecological significance of the partial volumetric reduction of hyporheic habitat

3. Trophic effects of reduced invertebrate (*hyporheos*) production due to reduced habitat volume (e.g. What are the impacts to stream productivity and salmonid production?)

4. Effects of channel morphology simplification (e.g. straightening, LWD snagging, vegetation removal, bedform simplification) on hyporheic exchange processes (multiple scales)

5. Effects of altered microhabitat hyporheic flows (upwelling and downwelling) on benthic invertebrates and lithophilic vertebrate spawning (e.g. salmonids)

6. Effects of altered sediment transport regimes and substrate condition on hyporheic processes

   - Effects of channelization and bed paving / armoring on vertical exchange processes

   - Effects of fine sediment deposition on vertical and horizontal exchange processes

7. Ecological effects of altered nutrient dynamics and spiraling due to channelization specifically in the Pacific Northwest and Washington State

8. Effects of riparian vegetation removal on water quality and fluxes of solutes through hyporheic zones and rivers in Washington State

9. Effects of altered hyporheic flows and water/nutrient availability on riparian vegetation communities

10. Effects of different traditional engineering and modern bioengineering bank stabilization structures and techniques on hyporheic exchange processes

    - ☐ Do some structures and techniques alter hyporheic processes less than others?

11. Other land uses associated with channelization that effect hyporheic ecology

    - ☐ Floodplain development, paving, riparian logging, grazing

12. Effects of different riparian vegetation communities on hyporheic ecology in Washington

    - ☐ Conifer, hardwoods, pasture, exotic species, conifer monocultures

13. Do hyporheic exchange processes still occur in heavily channelized rivers (revetments and levees)?

14. Effects of reduced floodplain interactions on hyporheic and perirheic processes

    - ☐ Lost overbank water, sediment and nutrient storage potential

15. Impacts of lost opportunities for the creation or occupation of potential hyporheic habitat (e.g. paleochannels) along the hyporheic corridor or channel migration zone

16. General hyporheic zone processes in the many diverse watersheds of Washington State

Habitat Protection and Mitigation Techniques

Background

While the problems associated with aquatic species decline are often complex and confounded by multiple issues rooted in the biological, physical, and social sciences, the importance of physical habitat as the foundation of healthy aquatic ecosystems has recently become the major focus for active restoration and rehabilitation projects. Aquatic communities are very complex and their health does not solely ride on the integrity of their physical habitat. However, as humans continue to modify the physical structure of landscapes and their associated processes, the physical habitat of aquatic ecosystems has become exceptionally degraded, resulting in a need for habitat-based restoration. Altering the fluvial geomorphic processes and structure of aquatic ecosystems, especially by channelization, flood control, and land reclamation projects, has resulted in much of the science of river restoration emerging from the perspective of hydrologists and geomorphologists. However, fluvial systems are not affected only by hydrologic and geomorphic processes. The interaction of vegetation and succession with hydrology and geomorphology and recognition of the structure of aquatic communities and biological requirements of individual species makes the process of truly restoring aquatic systems very complex. This section on habitat protection, enhancement, and mitigation techniques emphasizes the processes that restore (Beechie and Bolton 1999) the physical templates of aquatic ecosystems, but the reader is strongly encouraged to acknowledge the true nature of the problem that goes beyond the scope of this white paper.

Probably the simplest, most direct and least expensive way to improve the integrity of stream systems affected by channelization and confinement is to alter or halt the current management strategies that are a partial cause of continued habitat degradation. Management strategies that encourage and allow natural adjustment and healing processes to evolve over time tend to succeed because of the positive feedbacks derived from working with the natural tendencies of a fluvial system rather than against them (Ebersole et al. 1997). These management strategies tend to fall under the mitigation categories of avoiding, reducing or minimizing potential impacts. In areas with numerous degraded waterways and limited resources, natural recovery may be the most efficient and pragmatic process towards the recovery of stream systems over wide geographic areas (Brookes 1995). However, natural healing processes can take upwards of 100 years in some extremely degraded systems (Bayley 1991; Kern 1998) and without some degree of human intervention might never return to a state close to previous conditions. Allowing natural recovery to take place could permit ‘surrogate’ habitats to develop that provide increased habitat values compared to the current degraded conditions (Dennis et al. 1984). Therefore, natural recovery processes should be encouraged where feasible to maximize existing potential and that active restoration, rehabilitation or alternative management should be pursued in areas where recovery is slow, where full restoration is desired, where expedited habitat recovery is needed due to the threat of species extinction or where special human needs or opinions call for active management and only partial rehabilitation (Brookes 1995).

Streamside Vegetation Removal

For hundreds of years, it has been common practice in channelized river systems with extensive levees and revetments to maintain the channelization structures by keeping them clear of vegetation, especially woody riparian vegetation (Nolan 1984). Vegetation removal can either be a direct management goal or an indirect consequence of other procedures such as channel straightening or bank protection works. The rationale for vegetation removal includes access to levees for inspection, flood fighting, rodent burrow reduction, prevention of root induced piping (the lateral movement of water through large soil macro pores), reduced soil loading due to vegetation, decreasing erosion due to soil exposure following tree windthrow and decreasing frictional resistance to maintain flood conveyance (Shields and Gray 1992; Nolan 1984). Many government managers, land owners and flood control districts have been reluctant to allow vegetation to grow along levees and revetments due to the perceived risk of failures induced by the presence of vegetation.

Traditional levee and revetment maintenance practices in the United States and in many countries worldwide involve clearing vegetation annually for reasons noted above. This is usually accomplished by burning, mowing, hand clearing and herbicides, which act to keep the vegetative succession at an early state. The plant community tends towards one dominated by weeds, annual grasses and other disturbance tolerant species capable of surviving between semi-consistent maintenance schedules (Daar et al. 1984). Many civil engineers and maintenance operators ignore importance of most types of vegetation on levees and revetments. However, it has long been known that shallow root systems of grass sod serves to protect the surface of levees and some parts of revetments from surface erosion. In many instances, exotic or native grasses have been actively cultivated along levee margins to enhance the stability of the structure (Nolan 1984; California DWR 1967). The soil binding ability of vegetative root systems has long been recognized along stream systems and hillslopes and was reviewed in the previous section in this white paper. Vegetation on levees may also prevent the differential drying and settling of soil following high flow events by evenly drying the soil through transpiration. This drying effect reduces crack formation (Daar et al. 1984). During the hot months of summer, the riparian canopy also may shade the levee surface and reduce the development of cracks due to the heat (Daar et al. 1984).

However, to maintenance operators, the apparent negative effects of some types of vegetation have outweighed the positive. This is indicated by U.S. Army Corps of Engineers and state flood control agency standards, “trees which attain large growth should never be permitted to become established on the levees [and revetments]” (Nolan 1984).

The ecological effects of vegetation clearing have been well documented (Marzolf 1978; Shields and Nunnally 1984; Simpson et al. 1982) along with the importance of riparian vegetation for bank stabilization, habitat creation and nutrient dynamics (Kondolf and Curry 1984; Knight and Bottoriff 1984). Due to the growing concern for riparian and aquatic habitat degradation and the questioning of the effects of vegetation on structural integrity and conveyance, numerous authors and agencies have revisited the topics of clearing and snagging over the last several decades in search of feasible alternative management strategies (California DWR 1967; Gray and Leiser

1982; Gore and Petts 1989; Shields 1991; Gray et al. 1991; Shields and Gray 1992). Many of these studies have documented the potential ecological and structural benefits of allowing volunteer recruitment of vegetation, rehabilitation of vegetation on levees and revetments, and incorporating biotechnical methods into structural design.

Shields (1991) also noted the relative influence of vegetated revetments on the conveyance capacity of channelized river channels. In medium to large sized channels, the percent of the wetted perimeter occupied by revetments and potentially woody vegetation is only 10-15% of the total. Shields states that incorporating vegetation into revetments will only have minor influences on the roughness characteristics of the channel. He also suggests that riparian vegetation could be pruned to create a pattern of trunks to further minimize the resistance to flow. Masterman and Thorne (1992) provide a theoretical approach to predict the effects of grass and shrub bank vegetation on the discharge capacity of channels with compound roughness (vegetated banks and sediment-bed streams). They incorporate established engineering equations for roughness, channel hydraulics and vegetation into a general methodology to predict changes in capacity in channels with different width-depth ratio, amounts of bank vegetation and seasonal changes in vegetation growth. In their first application example, which holds vegetation stiffness (~ roughness) constant at a moderate level while varying the width-depth ratio, they conclude that the discharge capacity of the near bank zones (as a percentage of the total channel) only becomes significant (>5%) in channels with width-depth ratios of less the 9. Their second example analyzes changes in stiffness and width-depth ratio and their effects on discharge reduction. Their results indicate that for fully grown, dense stands of typical riparian vegetation (except for large trees), channel capacity reductions are less than 10 % for channels with width-depth ratios greater than 16. Capacity reduction is even less for channels with width-depth ratios of 20 and 30 (8% and 6% respectively) while dense vegetation may reduce discharge capacity up to 38% when the width-depth ratio is 5. These examples indicate that for most medium to large stream channels that have width-depth ratios greater than ~12 (Rosgen type B, C, D, DA, and F type channels (Rosgen 1994)), the percent reduction in discharge capacity due to dense vegetation is minimal to insignificant. However, in small, narrow, densely vegetated channels with width-depth ratios closer to 5 (Rosgen type A+, A, E, and G) the conveyance capacity may be significantly reduced by dense riparian vegetation. Masterman and Thorne (1992) recommend using their methodology or similar techniques for individual channels of concern to properly gage the effects of vegetation on discharge capacity. Once the analysis is complete, resource managers can properly determine whether the benefits gained by vegetation clearing for conveyance are truly significant or whether the benefits are outweighed by the economic cost of maintenance, the stability benefits of the vegetation and environmental effects of vegetation clearance.

On the Sacramento River in California, Shields (1991) found that in many cases the presence of woody riparian vegetation enhanced the soil shear strength of revetments and did not affect the performance of the structures during large discharge events. However, he warned of the complex interactions of vegetation and structural integrity and suggested that local vegetation, soil, stability and hydraulic conditions should be used to determine the effectiveness of vegetated revetments. During a more detailed study on the Sacramento River, Shields and Gray (1992) investigated the influences of different types of vegetation communities on the integrity of sandy levees (earth embankments). They found that the highest soil protection was afforded by vegetation with high root densities at shallow depths. While herbaceous cover such as grass fits into this category, he also found that woody species such as willow (Salix spp.) and elderberry (Sambucus spp.) had similar root densities at shallow depths. Woody species also have larger root densities at greater depths which can help prevent deep-seated sliding, slumping and riverward failures. As a potential compromise and rehabilitation strategy for unvegetated levees, Shields and Gray (1992) suggest that native woody shrubs and small trees afford the best protection for structural integrity while providing valuable habitat resources without the possible problems of windthrow associated with large trees.

In some case, large woody vegetation and riparian corridors along the levees and revetments may actually improve the structural stability and resistance to failure of levee systems. This has been documented on the Missouri River by Dwyer et al. (1997). Following the 1993 floods, an inverse relationship was found between the width of the riparian corridor on the riverward side of levees and the failure of those levees. Levees with woody corridors upwards of three hundred feet on their riverward side significantly reduced the linear failure rate during the floods. Dwyer et al. (1997) attributed the increase in levee stability associated with wide riparian corridors to two important hydrogeomorphic-vegetation interactions. First, the increase in shear strength of the soil due to the root fibers of dense stands of woody plants significantly reduces erosion as long as the vegetation is not undermined by flowing water or incision (Shields et al. 1995a; Shields and Copeland 1990). Secondly, the drag associated with healthy woody stream corridors can significantly dissipate energy and reduce local velocities. Beasley et al. (1984)(in Dwyer et al. 1997) report that a four-fold reduction of bed shear stress is associated with reducing the velocity by half. This reduction of shear stress due to the presence of woody riparian corridors can significantly reduce the erosion potential of stream banks and thus the failure of levee systems (Dwyer et al. 1997).

Despite some fairly obvious evidence of the benefits of vegetation on levees and revetments and no direct evidence of failure due to the existence of riparian vegetation (Carter and Anderson 1984), there is still widespread concern for allowing vegetation, especially large native trees with shallow root systems, to grow directly on the faces of levees and revetments. One solution to this dilemma is to incorporate vegetation and large trees into the design of flood control structures (before or after construction) on a site-specific basis. Another is to accommodate the increased costs associated with levee maintenance, inspection and habitat improvement sometimes associated with the existence of woody vegetation. One of the main arguments for not allowing woody vegetation growth on levees and revetments is due to the increased time (and thus cost) needed to inspect structures with moderate to dense vegetative cover (Carter and Anderson 1984). However, if additional funding (i.e. time) is available, then maintenance and inspection needs can be met on vegetated levees and revetments.

Daar et al. (1984) proposed an integrated protocol for levee maintenance that accommodates riparian vegetation preservation and rodent control while allowing for the selective removal of vegetation. During an early state-government mandated study of the possible inclusion of vegetation on levees on the Sacramento River, the California Department of Water Resources (1967) conducted several tests to determine the best designs for the transformation of flood control levees into multipurpose structures (flood control, erosion control, esthetics and wildlife habitat) using vegetation. Their experiments consisted of determining the feasibility and cost of establishing different communities of vegetation, primarily exotic grass, shrubs and trees, on flood control levees. They specifically avoided testing the suitability of certain native species that they deemed incompatible with levee design such as cottonwoods, willows and alders despite their final determinations these native trees could be compatible with levees if maintained properly (Dennis et al. 1984). They concluded that exotic vegetation may be established and/or native vegetation may be left on levees if they are maintained properly to ensure the structural integrity and inspection capability of the levees and revetments. However, it should be noted that the introduction of exotic species to riparian zones may hasten their spread (Ferrari 1993) and lead to other problems in the floodplain. Cost is one of the primary concerns in implementing the revegetation and maintenance needs of multipurpose structures. In many cases even slight cost increases were prohibitive for existing maintenance budgets and thus relatively few changes in maintenance procedures were implemented following the study.

If landowners, managers and society feel that the environmental benefits of riparian communities along existing revetments and levees are worth the extra cost, then allowing volunteer recruitment, incurring the increased maintenance costs or utilizing the array bioengineering design and rehabilitation techniques for levees and revetments could be a worthy pursuit. As Whitlow et al. (1984) state in their cynical but realistic report on levee maintenance in California, the true solution to improving riparian habitat along channelized river systems involves changing the public policies and views towards riparian system management to accommodate the fiscal and logistical constraints of implementing habitat improvement.

In-channel Vegetation Removal (Snagging)

The ecological effects of snagging have also been well documented (Marzolf 1978; Shields and Nunnally 1984; Simpson et al. 1982). For the last two hundred years it has been common practice to remove woody debris and snags from unchannelized and channelized river systems (Sedell and Froggatt 1984). The rationales underlying the practice of snagging include navigation, timber and firewood collection, floodplain drainage, recreation (canoeing and kayaking), structural protection, fish passage, frictional resistance, and flood conveyance (Marzolf 1978; Shields and Nunnally 1984; Simpson et al. 1982). Over the last several decades in the United States and other countries, but especially in the Pacific Northwest, the scientific understanding of the biological and physical importance of LWD in river systems has changed the way we view rivers (Keller and MacDonald 1983 and 1987; Abbe and Montgomery 1996; Abbe, 2000). The valuable role of LWD in river systems is now widely recognized and new ways of dealing with the concerns over wood removal and habitat retention have been developed over the last few decades.

Shields and Nunnally (1984) described some potential ecological benefits of modified snagging techniques in river systems and provide guidelines for implementing alternative techniques. They call for a site-specific approach to snagging using an interdisciplinary team to selectively decide which pieces of wood have the potential to be nuisances and need to be removed. This technique could mitigate for the past indiscriminate removal of wood from the channel by inexperienced management personnel. The use of hand tools (chainsaws), small boats or barges and winches to remove undesired pieces is recommended instead of heavy equipment. They suggest reducing the size of wood so that the river channel can transport it more easily rather than removing wood entirely. If it is necessary to fully remove snags from the river channel they recommend using the wood for bank stabilization, channel training, and habitat rehabilitation projects using bioengineering techniques.

Shields and Nunnally (1984) also note the relative importance of LWD and snags in contributing to increased flood height along river channels. While their investigation of existing literature does indicate that clearing and snagging can reduce frictional resistance (Manning's 'n' coefficient), especially in smaller channels, they indicate that snagging has little benefit in improving flow hydraulics and reducing flood heights in larger river systems. The flood reduction benefits per unit effort through snagging in large river systems are outweighed by the lack of significant results and environmental consequences. They indicate the true benefits of snagging in large rivers may only be realized if navigation is a social and economic priority.

The application of these guidelines in channel maintenance and design is still difficult due to the lack of knowledge in determining the exact effects of partial snag removal on conveyance and the tradeoffs between environmental protection and economic concerns (Shields and Copeland 1990). However, knowledge of the incremental effects of snag and bank vegetation removal on aquatic habitat degradation and conveyance benefits is slowly receiving more attention in research fields (Smith et al. 1992). In a more complex analysis and view of the effects of woody debris on flow resistance, Shields and Gippel (1995) provide a technique for computing the friction factors (a composite measure of channel roughness) in channels with varying levels of LWD. Friction factors are incrementally divided into three components: bends, bed, and debris. The contribution of debris to resistance can then be calculated using a field estimate of debris density, an estimate of a drag coefficient and channel geometry variables. Their results show that theoretical calculations of friction factors give reasonable estimates of measured friction factors in channels with significant wood debris. This technique may be useful to resource managers interested in calculating the hydraulic effects of woody debris removal on flood conveyance and weighing the benefits of proposed actions. However, the mathematical details of such calculation may prevent the widespread use of such techniques. From two case studies, Shields and Gippel (1995) found that snagging only provided modest increases in conveyance (5-20%). They also warned that the benefits of LWD removal declines over time due to additional wood recruitment from bed scour and bank erosion, creating a negative feedback cycle for maintenance.

The complex responses of fluvial systems to debris removal may result in undesired outcomes. Several studies indicate that benefits of snagging to improve conveyance decrease at higher flows when friction factors for cleared vs. un-cleared reaches converge to the same value (Hecht and Woyshner 1987; Shields and Gippel 1995). Smith et al. (1993) found that alternate bar formation following debris removal actually increased the channel resistance due to the increase in the bed (including bedforms) component of the composite friction factor. Other studies show the opposite trend with no significant channel stability issues or unexpected results following debris removal (Shields and Gippel 1995). Therefore, site-specific approaches should be taken to address the issues of LWD removal. This will allow the determination of all possible benefits, impacts and drawbacks to proposed actions and encourage the development of potential alternative strategies to traditional channel maintenance and management practices.

Natural Recovery/Passive Restoration

As previously mentioned, management activities that relax the human constraints on channelized and degraded river systems can promote the geomorphic and biologic succession necessary for recovery (Ebersole et al. 1997). The resiliency of native riparian communities can be tremendous. Natural hydrogeomorphic processes can also rebound following channelization promoting the re-creation of habitats suitable for aquatic and riparian species through meandering and pool-riffle formation (Keller 1978). However, in many cases the continued maintenance of channelized rivers through dredging, re-straightening, clearing and snagging, and bank protection maintenance has prevented the natural recovery of many channelized rivers worldwide. Thus, modifying or ceasing maintenance strategies can drastically improve the recovery potential of river systems.

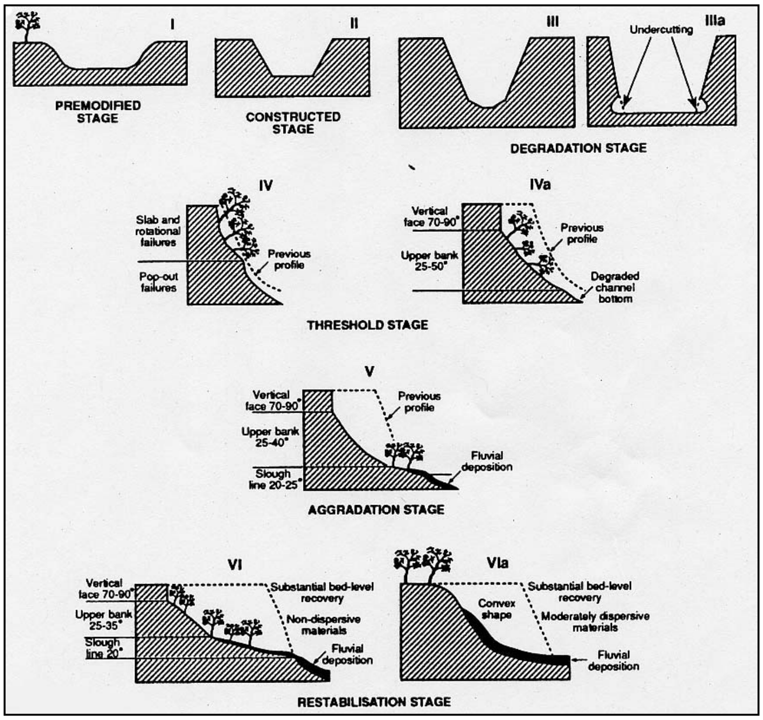
Simon and Hupp (1987) described the evolution and recovery patterns of channelized lowland streams in the Midwest following the halt of vegetation clearing and levee maintenance practices. While the recovery process and evolutionary pattern will not be identical for every channelized stream, the conceptual value of their model for the potential response and recovery of channelized streams is important in realizing their potential. As described previously in the section on the Effects of Channelization, a channel undergoes a series of morphological adjustments after channelization. This process is similar to the rejuvenation of streams following tectonic uplift (Leopold et al. 1964; Hupp 1992). An increase in gradient, migration of headcuts upstream and subsequent erosion and deposition downstream typically follows channelization. Associated with this process are the evolution of channel form and the differential creation of habitat sites for riparian vegetation. Simon and Hupp (1987) developed a successional stage model from their observations of channel recovery patterns in western Tennessee River systems (see Tables 3 and 4 below).

According to their channel evolution model, readjustment and channel evolution begins soon after channelization with the river attempting to regain its natural slope, sinuosity and sediment transport balance. After initial downcutting, the banks are undercut which leads to slumping and bank failure. This results in channel widening and aggradation of excess sediment in the channel. As this sediment is reworked, point bars begin to develop again as sinuosity increases. Eventually, the channel will establish a new floodplain at a new equilibrium and base level. If the channelized river system is continuously maintained by dredging, clearing, snagging, re-adjusting, and re-straightening, the river could become stagnant in the lower stages of degradation and never proceed to or achieve the recovery stage where significant revegetation takes place. This was the case for many years in western Tennessee with several different cycles of construction work. However, as of 1970, the U.S. Army Corps of Engineers stopped their dredging and channelization work and drastically reduced their maintenance program (Hupp 1992). This has allowed for the evolution of the channel through the different recovery stages and the dramatic improvement of riparian and aquatic habitat. For a detailed account of channel evolution processes and recovery following channelization, see Simon (1994).

Table 3. Simon and Hupp 1987A

Stage No.	Stage Name	Dominant processes: Fluvial	Dominant processes: Hillslope	Characteristic forms	Geobotanical evidence
I	Premodified	Sediment transport; mild aggradation; basal erosion on outside bends; deposition on inside bends.		Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering.	Vegetated banks to flow line.
II	Constructed			Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank.	Removal of vegetation(?).
III	Degradation	Degradation; basal erosion on banks.	Pop-out failures	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.	Riparian vegetation high relative to flow line and may lean toward channel.
IV	Threshold	Degradation; basal erosion on banks.	Slab, rotational, and pop-out failures.	Large scallops and bank retreat; vertical face and upper bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank.	Tilted and fallen riparian vegetation.
V	Aggradation	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks.	Slab, rotational, and pop-out failures; low-angle slides of previously failed material.	Large scallops and bank retreat; vertical face, upper bank, and slough line; flattening of bank angles; flow line low relative to top bank; development of new flood plain(?).	Tilted and fallen riparian vegetation; reestablishing vegetation on slough line; deposition of material above root collars of slough-line vegetation.
VI	Restabilization	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition on flood plain and bank surfaces.	Low-angle slides; some pop-out failures near flow line.	Stable, alternate channel bars; convex-short vertical face on top bank; flattening of bank angles; development of new flood plain(?); flow line high relative to top bank.	Reestablishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough line and upper bank vegetation; some vegetation establishing on bars.

Table 4. Simon and Hupp 1987B



This conceptual evolutionary model shows the potential of natural recovery if the existing management regimes are altered to accommodate the recovery process. However, Simon and Hupp's (1987) study did not address any of the potential constraints on allowing the full recovery of channelized rivers in other locations. Obvious conflicts could potentially arise due to the increased sinuosity, channel migration, levee or revetment erosion, overbank flooding, loss of streamside property and other social and economic values. While the potential for natural recovery exists, in many cases recovery cannot be allowed to fully proceed until the larger physical, economic and social issues are resolved.

Another passive form of restoration can be changes in grazing and pasture management (Rinne 1988). A study in Montana of a 10-year exclosure around a montane stream showed that stream bank vegetation and stability were markedly improved within the exclosure. For additional information on impacts of livestock on riparian areas and potential management alternatives refer to Kaufman and Krueger (1984) and Platts (1991).

Alternative Construction/Design Practices to Mitigate Impacts

Minimization of Impacts During Design and Construction

As with the alternative management section where altering certain management practices or promoting natural processes was encouraged, this section on alternative construction and design practices utilizes some basic design and construction guidelines that when followed, minimize the impacts of channelization on aquatic resources.

Nunnally (1978) argues for a new design approach to stream channelization projects that promotes stream channel preservation during construction. He suggests:

1. Straightening the channel and increasing the slope as little as possible.

2. Promoting bank stability by leaving as many trees as possible, minimizing channel reshaping, early seeding of native grass or other vegetation in disturbed areas and judicious placement of riprap.

3. Emulating nature in designing channel form.

Lund (1976) also offers some general design and mitigation techniques for cold-water trout streams:

1. Alter natural channels only when absolutely necessary and keep alterations to a minimum; preserve the meandering course

2. Retain trees and shrubs to provide bank stability and shade; replace topsoil

3. Above high-water level, cover riprap with soil and revegetate

4. Place mitigating devices in gravel-bed rivers at 5-7 channel widths to emulate the pool-riffle sequence of natural channels

5. Carefully locate mitigating devices across a channel section to provide effective aquatic species habitat

6. Randomly place rocks to create larger mid-channel pools

Keller and Brookes (1984) offer some general design guidelines for designing meandering channelization projects:

1. Estimate potential channel stability following construction

2. Design for a two-stage channel when flood control is an objective

3. Use vegetation as a means of stabilizing streambanks and floodbanks whenever feasible

4. Minimize channelization

5. Do not over design

6. Develop a reverence for rivers.

While the importance of incorporating environmental features into design practices is now widely recognized and best management practices have been used since the early 1970s to minimize onsite construction impacts, there still is a lack of universal or specific guiding design principles that are consistently implemented during river engineering projects. Several new approaches to river engineering design have emerged recently that simultaneously accommodate flood protection and environmental objectives. These new approaches effectively integrate higher levels of physical heterogeneity and habitat complexity into channel design without compromising the needs of humans on the landscape (Shields and Copeland 1990).

The emerging discipline of Ecological Engineering provides some basic design principles for integrating societal and ecological needs in patchwork-mosaic landscapes with complex land use.

Bergen et al. (in press) suggest 5 key principles of ecological engineering design:

1. Design based on ecological principles
2. Design for site-specific context
3. Maintain independence of design functional requirements
4. Design for efficiency in energy and information
5. Acknowledge the values and purposes that motivate design

Such a combination of highly constrained physical design systems (engineering) and highly unconstrained natural ecological processes requires a new way of thinking about design problems.

Preservation of Channel Morphologic Features

As noted earlier, channelization and channel straightening usually involve reducing the longitudinal stream length, reducing the sinuosity and increasing the gradient. Significant ecological impacts result from this simplification of channel morphology and habitat. If channelizing or confining the river is absolutely necessary, there are several construction and design alternatives that are preferred to traditional methods.

One key alternative to mitigating the initial impact of channelization projects is to preserve the original meander bends of the river whenever possible. While the construction costs (usually determined by the dollar per linear foot of the project) are typically higher for constructing meandering channel alignments, the long-term ecological and maintenance benefits of this technique will probably outweigh the initial increase in construction costs (Brookes 1989; Keller and Brookes 1984). Minimizing the stream length reduction usually associated with channelization projects moderates the complex geomorphic responses associated with a reduction in length and an increase in gradient. While meander preservation does not alleviate all problems associated with channel confinement, it does reduce some of the impacts. Keller and Brookes (1984) note that meander preservation has been utilized successfully in the United Kingdom for the last sixty years. This practice has reduced the widespread stability problems associated with traditional channelization and straightening despite the loss of smaller channel unit features such as pools and riffles. Channelization projects that are compatible with the natural tendencies of river systems, especially larger scale fluvial patterns like meanders, tend to be more stable, require less maintenance, and are more ecologically productive than traditional projects (Brookes 1989). Therefore, any initial effort to preserve the existing morphology will benefit the system in the long run.

Another important preservation technique during channelization design and construction is the preservation of smaller channel unit features such as existing pools and riffles whenever possible. Traditional channelization projects typically not only straighten stream channels but also simplify the in-channel topographic features associated with natural channels. Degraded, channelized stream systems often attempt to rebuild and regain their natural sinuosity and topographic feature (e.g. alternate bars) following channelization (Jaeggi 1989). Often recovery is never complete due to the total destruction of pre-existing habitat unit templates and larger scale alterations. In addition, the rehabilitation (but not complete restoration) of in-stream habitats by river managers often includes the reconstruction of pool-riffle or other habitat units, which typically has mixed results (Brookes 1989). Therefore, it is recommended and practical to retain as many of the existing natural in-stream habitat units as possible during channel manipulation practices (Nunnally 1978).

Partial construction and modification of only one half of the channel can significantly reduce the environmental impacts associated with complete channelization procedures. In many countries, the practice of modifying only one bank and leaving the opposite bank untouched has become common practice (Brookes 1989). This practice promotes the partial preservation of aquatic and riparian habitat and mitigates the loss of vegetation, shade, aesthetic appearance, bank stability, and habitat forming processes. In many cases, bank protection, straightening or channel widening procedures are alternated from one side of the river to the other, leaving a patchwork of unmodified sections that partially mitigate the loss of aesthetic integrity and sensitive habitats (Brookes 1989). Often, this practice involves bank protection/stabilization works such as riprap revetments only on the outside bends of meandering river systems, while leaving the point bar and riffle sections unmodified. These untouched areas can serve as important refuges for wildlife and still provide many of the functions of the pre-disturbed fluvial system.

However, while the impact of this method of channelization is less extreme than complete channel straightening or armoring, it still can have significant short and long-term consequences. Protecting just the outside bends of migrating river channels is still a form of channelization, though often masked by its site-specific nature. Many river systems throughout the world have been effectively channelized or confined by the slow, cumulative process of incremental bank armoring over time by small, site-specific projects. Meander migration and cut-bank erosion is an important mechanism in which rivers dissipate energy and maintain quasi-equilibrium. When this processes is truncated by reducing meander rates, the river is forced to adjust to new conditions, which often result in unintended consequences. Specifically, the reduced rate of meander migration inhibits point bar development and the creation and maintenance of new habitat in the unmodified portions of the reach. While the short-term effects might not be directly evident, the long-term effects can include the die off of riparian communities due to the lack of habitat forming processes, which can lead to an altered community structure.

Larsen et al. (1997b) modeled the geomorphic consequences of alternating riprap revetment structures on the Sacramento River. While their model does predict the intuitive effect of riprapped meander bends in reducing sinuosity in some cases, they also found that in many locations, the presence or absence of alternating riprap had little effect on long-term (50-100 years) sinuosity and wavelength amplitude due to channel migration away from the protected areas. This indicates that in some river systems, the benefits of using alternating riprap for erosion protection may be ephemeral because of the adjustment processes of natural fluvial systems. In these situations, natural recovery may be fairly rapid, but the human motivation for accelerated bank protection measures following migration may reduce the mitigating effects of alternate bank modification. Therefore, while this technique is preferred over complete channel modification, the long-term human benefits and costs may be limited and other methods of erosion and flood protection are recommended.

Vegetation Incorporation into Levees, Revetments and Other Embankments

As stated in the Streamside Vegetation Removal section, there are numerous alternative structural and design methods that incorporate different types of vegetation on levees and revetments. While this section will address some of the basic techniques to minimize environmental impacts during the design and construction of riverine projects, it will not provide detailed information on the design of riverine structures or the numerous hydrologic or engineering issues that surround their construction.

In many cases, levees and revetments can be modified into multipurpose structures to accommodate different types of vegetation. A more traditional method favored by most engineers for accommodating woody vegetation on flood control structures is to overbuild or enlarge the levee or revetment (Carter and Anderson 1984). This effectively provides a zone for roots and vegetation on the landward side of the structure while also ensuring the integrity and margin of safety of the structure. However, the unnatural location and function of these surrogate vegetation zones make them less than ideal for the establishment of native riparian vegetation (Nolan 1984). Due to the reduced flood regime, altered substrate conditions and reduced moisture availability, these levee sites are usually suitable only for facultative upland species rather than typical streamside, riparian communities that prefer moist to wet conditions. While this type of integration of structural function and habitat still does not provide all the attributes of a properly functioning riparian zone, it does provide surrogate vegetation habitat and ecosystem function of greater value than unvegetated structures. In the Pacific Northwest, the establishment of conifers in this overbuilt zone of levees could easily be accommodated in most situations and provide the long-term recruitment of LWD needed to promote habitat complexity in simplified river systems.

Another method of levee and revetment design that incorporates vegetation is the construction or retention of a berm on the riverward side of the levee (Brookes 1989). Essentially, a two stage cross-sectional geometry is created on one or both sides of the river. The low flow channel confines the normal discharges of water and sediment while berm and high flow channel mimic the bank-full height and floodplain level of the pre-channelized river. The levee still serves as a flood protection structure for the surrounding pre-channelized floodplain. In some cases, the riverward slope and toe of the berm are revetted with stone to prevent erosion and migration of the low flow channel within the leveed river (Henderson 1986). The berm allows the development of a narrow riparian corridor on the riverward sides of the levee which serves many different functions. Structurally, the riparian vegetation supported on the berm protects the levee or revetment and berm from erosion and failure (Dwyer et al. 1997). However, where dense riparian vegetation develops and flood conveyance is a major issue, periodic, selective maintenance thinning is sometimes conducted, especially brushy undergrowth (Brookes 1989). Ecologically, the vegetated berms serve as surrogate riparian corridors that provide some of the same functions as natural riparian corridors.

Designing or retaining a two stage channel morphology greatly benefits the site-potential and thus the type of riparian community that can be established along a flood control structure in a modified stream. Certain riparian species, specifically of the family Salicaceae (cottonwoods and willows), have life history traits that are closely tied to hydrogeomorphic processes that produce moist, bare, sunny sites of newly deposited sediment along channel margins (Braatne et al. 1996). These seedling establishment sites are usually associated with three types of geomorphic disturbance processes: river meandering and point bar development, floodplain scouring and deposition, and channel abandonment (Scott et al. 1996). Unless meander bends and channel unit features are preserved during stream channelization, the only process available for the establishment of these species following channelization or bank stabilization is floodplain scouring and deposition. Traditional channelization procedures isolate the river from its natural floodplain and create steep banks with small surface areas and low moisture contents, which make vegetation establishment difficult if not impossible. By creating or retaining a berm on the inside of levees, a surrogate floodplain is created that allows for vegetation establishment following the inundation, scouring and sediment deposition on the berm. Consideration of habitat needs such as these during the design and construction of flood or erosion control structures can mitigate the long-term effects of streamside projects.

After channelization, berms and thin veneers of sediment can also develop naturally along embankments through deposition as the natural recovery processes progresses. Maintenance practices that permit the deposition of sediment on the riverward side of the levee or revetment embankment allow for the colonization of riparian vegetation and the effective buffering of the structure from the hydraulic energy of the river system (Shields 1991). This natural recovery process is especially common on channelized systems that are attempting to regain their original sinuosity and sediment transport regime. A larger scale and more geomorphically and ecologically functional version of a two stage cross-sectional design is the concept of constructing setback levees far enough from the active low flow channel to unconstrain the river system. This provides a more natural floodplain berm for the establishment of riparian vegetation, migration of the river, conveyance of water and sediment, and retention of floodwaters. This topic will be addressed in the active restoration section below.

Alternative designs of traditional channelization, flood protection, and erosion control structures such as rock revetment (riprap) have the potential to provide opportunities for the development of riparian vegetation. In contrast to traditional rock revetment methods that armor the entire height of the bank, ‘low rock revetment’ can be placed at the toe and lower banks of the embankment so that woody riparian vegetation can develop on the upper portion of the bank and possibly within the rock itself (Henderson 1986; Carter and Anderson 1984). Dennis et al. (1984) states that the height of the riprap is critical to the amount of vegetation that can be supported on the water face of embankments. This type of basic integrated design allows for the structural stability of the bank while also providing surrogate ecological and aesthetic benefits. This technique has proved to be very stable and effective in preventing erosion and flooding on the Sacramento River for the last sixty years (Henderson 1986). This method could also be used along or in conjunction with a berm as mentioned above. Sotir and Nunnally (1995) and Thorne et al. (1995) give a more detailed explanation of the potential uses of rock revetments and riprap in conjunction with vegetation and other bioengineering techniques (see also WDFW 2000).

Alternative Bank Protection Techniques

Over the last several decades, the use of alternative structures for bank protection, erosion control and flood protection has increased in popularity due to the perceived or realized reduction in ecological impacts. In the past, engineers and resource managers have had relatively limited choices in techniques that could be used for river engineering and flood control projects. These limitations were mainly due to a lack of integration between science and management along with societal pressure that promoted the protection of aquatic/riparian resources and the use of bioengineering techniques. For example, prior to the 1980's, governmental organizations such as the Soil Conservation Service and U.S. Army Corps of Engineers utilized a fairly short list of possible techniques for flood and erosion control. Environmental considerations and concerns were usually accommodated, by encouraging selection of the method with the smallest effect on aquatic and riparian resources.

Types of channel modification listed in ascending order of impact on fish and wildlife resources (U.S. Soil Conservation Service 1977, as cited in Brookes 1989):

1. Riprapping (placement of rock as bank protection)
2. Selective Snagging (selective removal of objects such as fallen trees)
3. Clearing and Snagging (removal of debris such as shoals and vegetation)
4. Widening (enlargement of channel by widening)
5. Deepening (enlargement of channel by deepening)
6. Realignment (construction of a new channel)
7. Lining (placement of non-vegetative, smooth lining)

While these methods are still used today, the techniques available to resource managers for river engineering, flood control and erosion control have expanded tremendously to include many different types of designs that more effectively integrate societal and biological needs. Techniques that have evolved out of the fields of bioengineering and restoration ecology over the last few decades have slowly permeated into the fields of river engineering and watershed science. While some of these design concepts and engineering techniques have been implemented in a variety of contexts and have helped to change the perception of many resource managers and land owners (Schnick et al. 1982; Patterson et al. 1984; Thorne et al. 1995), they are not in widespread use despite abundant literature, guidelines and manuals (eg. Gore 1985;

Johnson and Stypula 1993; Newbury and Gaboury 1993; Brookes and Shields 1996a; Slaney and Zaldokas 1997; Flosi et al. 1998; FISRWG 1998). Many resource managers are reluctant to use certain techniques, because of the lack of widespread implementation, field-testing, monitoring, and peer reviewed literature. When push comes to shove, many engineers and resource managers fall back to time proven "traditional or conventional" techniques and approaches due to either societal and economic constraints and pressures or a lack of experience in alternative procedures (Shields and Copeland 1990). However, the disciplines of bioengineering and restoration ecology are rapidly developing to meet the ecological and societal demands for alternative engineering procedures in fluvial systems.

Currently there are copious alternative bank protection techniques that can be used to partially mitigate the ecological effects of channelization, flood control and erosion control projects. As watershed science and bioengineering technology continue to evolve and develop, many new and innovative techniques will be added to the possible choices available to scientists, engineers and managers. While alternative bank protection techniques are strongly linked to natural hazard mitigation, ecosystem impact mitigation and partial or full river restoration, the review of these techniques is beyond the scope of this white paper. There are many detailed literature reviews, manuals, guidelines, reports, books and articles on the subject. In fact, most of the emphasis in stream habitat mitigation and restoration over the last fifteen years has focused on small scale, site-specific alternative bank protection techniques. Less emphasis has been placed on holistic riparian corridor management and watershed scale restoration, as will be seen below in the Active Restoration Section.

A partial list of the alternative bank stabilization literature is given in Table 5; synthesis of scientific information is left up to the reader. For a more complete review of specific design techniques, the reader is referred to the Channel Design white paper in the Guidelines for Aquatic Habitat Protection and Restoration series, the numerous references in this section and paper, and the references listed below. Of interest in these documents is the evolution of the science and practice of bank protection over the last decade leading up to the modern "state of the art" in bioengineering and integrated streambank protection.

Active Restoration and Rehabilitation Techniques

Full Restoration: channel geometry and habitat features

To regain or re-express the habitat complexity of riverine ecosystems that existed prior to channelization and confinement, one must look beyond site-specific enhancement projects and envision a given catchment as a holistic system and assess its potential for full restoration. In many highly developed catchments, complete restoration might seem like an impossible task due to the extreme changes that have taken place, especially in urban areas. However, it is imperative that one view catchments and ecosystems as fully restorable in order to develop a holistic restoration plan and vision that will help shape the path of future restoration steps. In many cases, this vision will never result in a full re-expression of habitat complexity, but it will help push the effort to enhance aquatic ecosystems as close as possible to their potential. Without such as vision, management and enhancement strategies are often doomed to fail as mere 'Band-

Table 5. Alternative bank stabilization references (See appendix A for full citations).

Author	Date	Title
WDFW	2000	Integrated Streambank Protection Guidelines
Crisp	2000	Trout and salmon: ecology, conservation and rehabilitation
Nichols and Sprague	1999	The Use of Long-Line Cabled Logs to Protect Eroding Stream Banks in Skagit County, Washington
FISRWG	1998	Stream corridor restoration: principles, processes, and practices
Flosi et al.	1998	California Salmonid Stream Habitat Restoration Manual
Cowx and Welcomme	1998	Rehabilitation of Rivers for Fish
Riley	1998	Restoring Streams in Cities: A Guide for Planners, Policymakers and Citizens
De Waal	1998	Rehabilitation of rivers: principles and implementation
Slaney and Zaldokas	1997	Fish Habitat Rehabilitation Procedures
Abbe	1997	Design of stable in-channel wood debris structures for bank protection and habitat restoration: An example from the Cowlitz River, WA.
Thorne	1995	River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone
Johnson and Stypula	1993	Guidelines for Bank Stabilization Projects in Riverine Environments of King County
Newbury and Gaboury	1993	Stream Analysis and Fish Habitat Design: A Field Manual
Orsborn et al.	1992	A Handbook for the Planning and Analysis of Fisheries Habitat Modification Projects
National Research Council	1992	Restoration of aquatic ecosystems: science, technology, and public policy
Hunter	1991	Better Trout Habitat: A Guide to Stream Restoration and Management
U.S. Department of Transportation	1989	Design of riprap revetment
U.S. Federal Highway Administration	1988	Use of Riprap for Bank Protection
U.S. Department of Transportation	1985	Design of Spur-type Streambank Stabilization Structures
Wesche	1985	Stream Channel Modifications and Reclamation Structures to Enhance Fish Habitat
New York State Department of Environmental Conservation	1985	Stream corridor management: a basic reference manual
Sheehorn	1985	Stream Habitat Improvement Handbook
Brown	1985b	Streambank stabilization measures for highway engineers
U.S. Army Corps of Engineers	1984b	Mitigating the impacts of stream alterations
Gray and Leiser	1982	Biotechnical slope protection and erosion control
Schnick	1982	Mitigation and enhancement techniques for the Upper Mississippi River system and other large river systems
Tarzwell	1934	Stream Improvement Methods

Aid' approaches to a declining system that suffered from a lack of planning and understanding of the natural potential. In many cases, it has taken 100's of years to degrade a catchment and it could take 100's more for it to recover (Bayley 1991). While partial restoration efforts and techniques are valid and beneficial in many contexts as identified throughout this paper, it is the goal of this section to uncover some of the emerging river restoration science that seeks to implement larger scale full restoration projects. Partial restoration and rehabilitation techniques will also be addressed below.

Armed with these ethical views and opinions, many resource managers, river scientists and restoration consultants have pushed for large, catchment scale restoration efforts that aim to fully restore large scale fluvial and habitat forming processes, especially in channelized lowland river systems. While there are relatively few documented examples of successful or unsuccessful large-scale river restoration projects, there is a wide variety of published literature that acknowledges and calls for alternative paradigms in river restoration (Gore and Shields 1995; Johnson et al. 1995; Ward and Stanford 1995; Brookes and Shields 1996a; Stanford et al. 1996; Ebersole et al. 1997). Most of the scientific information that emphasizes the importance of lowland river and floodplain restoration has been derived from the analysis of the relatively few intact lowland river floodplains that exist. For example, while the lower floodplain of the Mississippi has been reduced in size from is former grandeur, there are still large tracts of functional floodplain within setback levees that serve as models for restoring the millions of acres of lost floodplain due to levees upstream (Gore and Shields 1995).

Levee/Revetment Removal and Alternative Levee Functions

There are no examples in the literature of holistic catchment or sub-catchment scale restoration projects in lowland channelized river systems and many examples of site-specific rehabilitation projects, and only a handful of large reach and valley segment scale case studies of channelized lowland river restoration. While there may be examples of large-scale restoration projects, they either were not uncovered in the literature or are so new that they have not been well documented in the rapidly accelerating field of river restoration. Thus, the examples given below provide a sampling of case studies, in channelized river restoration, that are 'state of the art'. Some of the studies outlined below are ongoing restoration experiments that have little peer-reviewed literature published about them. However, it is projects like these that are at the cutting edge in channelized river restoration and are currently pushing the 'state of the art' and restoration vision toward the goal of catchment scale restoration.

For the last five years, The Nature Conservancy has been working on several experiments in levee removal, setback levee construction and levee breaching on the Lower Cosumnes River in the Central Valley of California (Florsheim and Mount, 2000; Whitener and Kennedy 1998). As part of their efforts to restore the integrity of their recently purchased 35,000 acres Cosumnes River Preserve, they have begun implementing their long-term plan to restore the river's access to its historic floodplain along most of the lowland river corridor. Since 1995, this has entailed taking parcels of agricultural land along the river out of production and breaching the flood retention levees in numerous locations. Accompanying this reconnection has been an intensive reforestation effort on the historic floodplain. To date, several publications, consultant reports, 'soft publications' and symposium papers have been written on the restoration effort.

Whitener and Kennedy (1998) documented the immediate use of the restored floodplain access and habitat by a wide variety of native and exotic fish species. Of particular importance was the utilization of the floodplain by species of special concern such as fall Chinook salmon and the endangered Sacramento Splittail, both of which utilized these floodplain habitats for either rearing or spawning and rearing, respectively. Their ongoing work will document the importance of these restoration techniques and help guide the design of future levee breach and removal projects. For example, while they documented the benefits of this restored habitat, they also found some inherent problems in the breaching design that contributed to the stranding and mortality of some fish. These learning processes in ecological engineering design are important to the success of future levee breaching and removal projects.

As a complement to the research on floodplain fish utilization on the Cosumnes, Florsheim and Mount (2000) from U.C. Davis documented the hydrogeomorphic response of the river to the levee breaches. They found that there was complex topographic response along the floodplain and river channel due to scour and deposition associated with the levee breach. They argue that this differential habitat creation following levee removal is what is needed to restore the remainder of the Lower Cosumnes River. Through continued levee breaches and setback levee construction, they predict that the newly unconfined river will be able to return to its original anastomosing morphology, where numerous and diverse channels are continuously formed and abandoned by channel avulsions (Florsheim and Mount 1999). Of particular concern along the Cosumnes however, is the fact that the levees have caused the river to incise into alluvial formations due to increased velocities, depths and shear stress associated with channelization (Vick et al. 1997; Reiner and Calhoun 1999; Andrews 1999). This has reduced the inundation frequency of the recently reconnected floodplain and influenced the restoration potential of the river corridor. However, if the levees are removed to unconfine the river, natural channel evolution process should result in an increase in sinuosity, meandering, and aggradation and therefore increase the inundation frequency of the restored floodplain (Simon 1994). This potential evolutionary response to setback levees on the Cosumnes River was also modeled by Andrews (1999), who predicted that shear stresses due to lower stage heights would be reduced by more than 50% if existing levees were setback to the edge of the 5-year floodplain (under a levee-free, 'restored bed elevation' hydraulic condition). In turn, the sediment transport capacity of the river would be significantly reduced allowing channel incision to cease. Subsequently, Andrews predicted that aggradation would occur promoting bed elevation restoration, reduced shear stresses and levee failure rates at new setback levees, reduced bridge pier scour and maintenance costs, increased meandering, increased gravel recruitment, increased floodplain inundation, increased groundwater recharge, and increased generation of riparian forests and floodplain habitats.

On the nearby Middle Sacramento River, another group of researchers from U.C. Davis has also been developing a levee setback geomorphic model that will allow the simulation and demonstration of the response of the fluvial system to levee removal and setback. The model is still in the production phase with little published literature (Greco 1999; Larsen, Greco and

Barker, in manuscript; Larsen, Mount, and Schaldow, in manuscript) and is currently being calibrated and tested along the Woodson Bridge subreach of the Sacramento River (and potentially the Cosumnes) where the loss of forest successional dynamics is a serious concern (Greco 1999). This new model is derived from past research that modeled the physical processes of large river migration (Mississippi and Sacramento Rivers) to predict the effects of different management strategies and structures on habitat formation (Larsen 1995; Larsen et al. 1997a; Larsen and Dietrich 1996; Larsen and Micheli 1997; Larsen and Greco 1998; Larsen et al. 1997b).

Key questions that this research should help answer include:

- What are the effects of different levee and revetment scenarios on the migration of large riverine systems?
- How do levees and revetments affect the long-term patterns of channel migration {e.g. Larsen et al. 1997b}?
- Where will setback levees have the greatest effects on attenuation of a flood wave?
- How much room is needed for flood control and the redevelopment of natural meanders?
- How far should levees be setback?
- What are the ecologic benefits of different setback levee scenarios when compared to land purchase costs in easements or fee title?

Numerous large-scale floodplain restoration projects have been conducted in Europe over the last decade. The most complete, well-documented and monitored project has been the restoration of the Brede, Cole and Skerne rivers in Britain and Denmark as part of the EU-LIFE demonstration project. Two agricultural rivers and one urban river were reengineered to restore the channel sinuosity and floodplain connectivity and functioning. These projects were documented in a series of papers related to the physical, chemical and biological integrity of the river sections (2-3 km long) before, during and after implementation (Sear et al. 1998; Holmes and Nielsen, 1998; Vivash et al. 1998; Kronvang et al. 1998; Hoffmann et al. 1998; Biggs et al. 1998). Key aspects of the projects included the removal of channelization structures (e.g. incised berms and levees), the re-meandering of the channels according to historic conditions, current conditions, constraints and professional knowledge, the reconfiguration of cross-sectional morphology, and the protection of property and infrastructure using setback berms, levees, light revetments and bioengineering bank stabilization techniques (Vivash et al. 1998). Comprehensive monitoring programs were developed to ensure and document success according to design functional requirements and constraints. Through monitoring, it was found that the restoration goals were achieved and the performance of the project exceeded expectations. At all sites, the floodplain connectivity and flood frequency were increase by reducing the bank-full channel capacity, deceasing the channel slope, lowering the bank level, and raising the bed level. Restoring the hydrologic connectivity with the former floodplain promoted the deposition of sediment on the floodplain and the retention of nutrients such as phosphorus and iron (Kronvang et al. 1998). Associated with the increase in flood frequency and inundation duration, was an increase in floodwater storage. While no major changes were seen in flood hydrographs pre and post implementation downstream of the project sites, peak water levels downstream were reduced and these projects were considered strategic in the defense of infrastructure flooding in the altered and developed catchments. As expected, the morphologic habitat diversity of the sites dramatically improved after re-engineering the rivers out of a simplified, straight plan form geometry. Pool-riffle sequences developed which increased the heterogeneity of both the bed sediments and biotypes/habitat units. Future monitoring of these restoration sites will shed more light on riparian community response to the restoration works through community succession (Biggs 1998).

While the above project descriptions sound straight forward, the morphologic channel response following geomorphic and floodplain restoration is fairly complex. Restoration implementation can be seen as a disturbance in and of itself and often involves channel evolution in predictable steps similar to Simon and Hupp's (1987) model of channel evolution following channelization and natural recovery. Sear et al. (1998) provide a geomorphic model of channel evolution following lowland floodplain restoration. They analyze the theoretical response of channel geomorphology in the upstream un-restored reaches of a project, the construction or restoration section and the downstream impact reach. Dependent evolutionary variables include sediment discharge, water discharge (downstream impact reach), width, depth, slope, sediment size distribution, sinuosity, bank stability, and vegetation colonization. This model was then tested on one of the EU-LIFE demonstration projects (River Cole, UK) during and after implementation. Preliminary results three years after restoration show that the evolutionary response following meander re-engineering and floodplain reconnection is predictable, but will differ locally depending on channel boundary conditions such as sediment size, bank cohesiveness, and vegetation recolonization. After initial erosion of construction material along the restoration reach and redeposition and aggradation in the impact reach, Sear et al. (1998) found that the trajectory of channel evolution was toward a more stable and diverse channel morphology with sediment yields returning to background conditions as sediment was redistributed and flushed out of the system. Evaluation and adjustment of this model to other channel types, locations and restoration projects is needed. In addition, design criteria for meander and floodplain restoration projects such as these needs to take into account local existing and historic condition, well beyond any design parameters derived from the literature (Rinaldi 1997).

Another large-scale river restoration project on the Kissimmee River, Florida (tributary to Lake Okeechobee and eventually the Everglades) has been in various planning, implementation and monitoring stages for the last twenty years (Toth et al. 1997). Channelization and impoundment of the river for flood control lead to the severe loss of aquatic resources (Buntz 1969; Obeysekera and Loftin 1988; Shen et al. 1994; Koebel 1995; Toth 1993; Cummins and Dahm 1995). Several demonstration projects have been implemented as pilot projects to guide elaborate future restoration plans. These pilot projects have shaped the current model (both mathematical and conceptual) for restoring the hydrogeomorphic regime that supported historic biodiversity

(Toth 1996, Toth et al. 1998). Major components of the restoration scheme include reinstating the hydrologic conditions that once existed in the now impounded river system, reshaping 14 km of the channel with new meanders and reconnecting historic meanders, reestablishing floodplain inundation and connectivity, removing levees and removing several water control structures. In total, 70 km of river and 11,000 acres of wetland habitat are set for restoration (Koebel 1995). Monitoring of restoration designs have been critical in ensuring that restoration goals are met and that the physical, chemical and aquatic systems are responding as expected and modeled (Toth et al. 1995; Belanger et al. 1994; Harris et al. 1995; Koebel et al. 1999).

Partial Restoration: Channel Geometry and Habitat Features

As stated earlier, in many stream corridors, the opportunity to fully restore a confined or channelized stream's channel geomorphology and habitat features to a pre-disturbance state are severely constrained either by economic, social, or physical conditions. Often, this is a result of human encroachment onto historic floodplains, which prevents the complete reconnection of the stream to its historic floodplain through levee removal or other methods, as mentioned in the Full Restoration section. Unfortunately, it is often a necessity and practical to forgo the complete restoration of a stream and concentrate on partial restoration and mitigation techniques that enhance channel geometry and habitat features to a higher level of integrity and functionality. This section will address the broad aspects of many techniques currently used to partially restore the integrity of stream habitats and ecosystems.

Partial Meander Restoration

As mentioned in the Ecological Effects of Channelization Section, channelization often results in a loss of in-stream habitat features. In a new channelized stream with a greatly reduced channel migration zone and active channel dimensions, it is still possible to partially restore a meandering pattern within the allowable active channel zone. Use of the entire historic floodplain or channel migration zone is preferred but not always feasible. Some broad restoration concepts will be presented here but the details of site specific design and restoration opportunities will be dictated by the potential of the site and extent of constraints such the as economic, social, or physical realities surrounding floodplain management.

It is now widely recognized by fluvial geomorphologists and most river engineers that straightened and channelized streams tend to be unstable over long periods of time and will attempt to regain some semblance of their original morphology following modification. It is rare to find straight channels in nature, especially in lowland areas. Many channel evolution models describe the development of a meandering pattern following some initial condition in nature where the channel is relatively straight (Keller 1972; Downs 1995). While these models are somewhat limited in their use in "natural" systems due to the usual lack of some "initial condition" where the channel is straight, they are very appropriate in predicting the response of stream channels following human induced straightening or rapid geomorphic evolutionary response (Simon and Hupp 1987), as previously discussed in the subsection in Natural Recovery. In recently channelized stream, small perturbations in the relatively uniform flow fields are caused by small-scale disturbances except in the most uniform channels. Turbulent flow vortices also develop due to frictional drag along the walls. These disturbances tend to be amplified or dampened in different locations of the channel, which in turn promote flow divergence or convergence. Thus, over time, meander growth is amplified by these positive feedbacks, which results in increased sinuosity and habitat unit formation.

In some streams with appropriate slopes and width-depth ratios, it is common for alternate bars to develop following channelization as the stream attempts to recover its balance between sediment size and slope, and stream slope and discharge (Lane 1955). Alternate bar formation following channelization is often incorrectly interpreted as a sign of aggradation (Jaeggi 1989), which then triggers more channel maintenance such as dredging. However, alternate bar development can be an integral part of the natural recovery of pool-riffle sequences of natural streams. A more sinuous, low flow channel migrating between alternate bars provides greatly improved habitat values for a variety of organisms compared to the previous plane-bed channel form. They also can be the beginning evolutionary form of a migrating point bar system within the larger confined channel. Depending on the discharge capacity of the channel, alternate bar bedforms can be encouraged and can lead to the development of a two-stage channel morphology with a small surrogate floodplain surface contained within the context of a larger channelized system. However, the concern over accelerated migration, bank erosion, aggradational buildup of temporarily stored sediments, vegetation colonization, and increased risk to flooding are obvious. This is especially true in urban areas where restoration must occur within a narrow corridor constrained by surrounding land use. These concerns are not inherent to all channels with developing alternate bars and need to be dealt with on a site-specific basis depending on the context of the catchment and water and sediment transport regimes. Furthermore, if erosion control or flood control is a concern, integrated bank stabilization techniques (bioengineering) can be incorporated to encourage meander development and provide a more holistic management approach to the fluvial system.

While the power of natural restoration processes of fluvial systems is often underestimated, it is sometimes necessary to speed the recovery process through active restoration, as in the case for endangered species. Within the context of an existing channelized stream with few opportunities for complete floodplain reconnection and meander restoration, there are numerous partial restoration techniques that can be used to promote increased aquatic habitat diversity.

The development of a more diverse meandering channel within a channelized stream corridor can promote habitat development. One method to promote the development of a sinuous channel within a channelized reach is to restore more natural cross-section morphology. Numerous different morphologies or configurations can be reconstructed or restored and only a few will be mentioned here. Many restoration examples in the literature indicate partial restoration success through re-grading of existing banks of the channelized streams (or existing low flow channel banks). Appropriate regrading provides asymmetrical cross-section geometry conducive to the formation of sinuous meanders (Brookes 1989 and 1995; Newbury and Gaboury 1993; Nielsen 1996). Asymmetrical cross-sections mimic the morphology of natural, meandering channels by directing the flow and promoting the formation of pool-riffle sequences. Typically, bank slopes on opposite sides of the channel are graded to different slopes, with 2:1 slopes on outside bends and 3:1 slopes on inside bends (Keller 1978). Water tends to converge along the 2:1 slope banks creating scour pools while the 3:1 banks promote divergence and deposition, mimicking point bar development, meander growth and floodplain development. Providing 2:1 slopes on both banks simulates crossover riffles where sediments are also deposited. For a lowland stream in Manitoba, Newbury and Gaboury (1993) successfully used a more skewed cross-section with 4:1 slopes on future inside bends. The Sacramento River Advisory Council (1989) also noted the importance of diverse bank slopes or fish slopes (5:1 slopes) at bank protection sites that create or simulate shallow bar habitat for juvenile salmonids during rearing and outmigration. The pattern of alternating bank slopes is typically repeated in a somewhat regular periodicity, with a typical pool spacing of 5-7 channel widths (Leopold et al. 1964). This initial bank geometry provides the initial perturbation and framework for the positive feedback and eventual growth of a meandering thalweg planform and desired habitat units. If left to their own development following the change in geometry, most lowland stream channels will recover to a more natural state as they redevelop pool habitat, point bar habitat, and small floodplain surfaces within the larger channel. The ultimate goal is to restore a morphology that facilitates morphologic stability and quasi-equilibrium in terms of the load imposed and the work done (Keller 1978). However, achieving this in degraded, channelized streams is often problematic due to altered hydrologic condition in areas of changing land use and altered disturbance regimes. In addition, if erosion is a problem due to excessive meander migration following reconfiguration, integrated bank protection techniques or bioengineering techniques can be used to stabilize the outside bends of the channel.

Another method that can be utilized to restore the cross-section geometry, habitat units, and potential planform sinuosity is the restoration of a two-stage channel morphology (complex cross-section) from a previously simplified channelized reach (Brookes 1989). This topic was already partially addressed above in the Full Restoration sub-section regarding setback levees and the Vegetation Incorporation into levees, revetments and other embankments sub-section, but will be reiterated and expanded on for clarification. Essentially, a two stage cross-sectional geometry is created on one or both sides of the river. The low flow channel confines the normal discharges of water and sediment while berm and high flow channel mimic the bank-full height and floodplain level of the pre-channelized river. The berm or bench allows for the development of a narrow riparian corridor on the riverward sides of the levee which serves many different geomorphic, ecologic and societal functions. Ecologically, the vegetated berms serve as surrogate riparian corridors that provide many of the same functions as natural riparian corridors and floodplains. Designing or retaining a two stage channel morphology greatly benefits the site-potential and thus the type of riparian buffer community that can be established along a flood control structure in a modified stream. Certain riparian species, specifically of the family Salicaceae (cottonwoods and willows), have life history traits that are closely tied to hydrogeomorphic processes that produce moist, bare, sunny sites of newly deposited sediment along channel margins (Braatnee et al. 1996), as is the case with two stage channels.

Restoring a two-stage channel morphology essentially jump starts the restoration and recovery process and allows the restoration designer to better predict and dictate channel planform geometry in tightly constrained situations. This practice is especially applicable in highly incised channelized streams, heavily degraded areas and in areas where extensive setback levees or floodplain reconnections are not feasible (Brookes 1990). Brookes (1987a, 1990, 1996) documented the successful design of a two-stage channel in Denmark that was severely incised and degraded by channelization for agriculture. Pulling back the steep banks of the incised stream, widening the channel significantly and reshaping a sinuous low flow channel with a floodplain berm and flood retention levee created a two-stage channel. While much of the historic floodplain was not reconnected to the stream, the surrogate riparian strip and floodplain was essential to partially restoring essential geomorphic processes.

Partial Floodplain Restoration

Human floodplain settlement and land use often prevents the full lateral and longitudinal reconnection of a river and its floodplain. This is often the case if many tracts of land are in different ownerships and land purchase costs or infrastructure removal costs are prohibitively high. If rehabilitation or restoration of aquatic habitat and floodplain connectivity is desired in these areas, the constraints of a particular location must be dealt with and partial floodplain/river restoration must be accepted, despite the vision to restore completely to site potential.

This has been the case for the Danube River in Austria (Tockner and Schiemer 1997; Tockner et al.1999a; Tockner et al. 1999b; Tockner et al. 1998; Schiemer et al. 1999; Hein et al. 1999; Heiler et al. 1995), where flood protection and navigation have prevented full floodplain reconnection and restoration. However, in a newly created park, the Alluvial Zone National Park, partial reconnection to historic but abandoned sections and back channels of the floodplain has been possible through the modification of existing engineered structures (Tockner and Schiemer 1997). Setback levees have been retained to ensure flood protection, but navigation training structures and interior levees have been breached and controlled in strategic locations to allow the three dimensional exchange of water, sediment, nutrients organic matter, and endangered aquatic organisms. The result has been the reconnection of exchange process into fragmented areas for more than half the year, which has improved habitat both in the river and backwaters. Hein et al. (1999) and Tockner et al. (1999a) document the positive response of planktonic productivity and species diversity respectively following the restoration of flood pulses. A positive response is also expected for endangered fish species, which have dramatically suffered due to their isolation from historic floodplain habitat due to channelization (Jurajda 1995). In-stream channel morphologic habitat, flood stage heights and property protection are expected to improve along the park due to reduced tractive forces and increased energy dissipation by the floodplain. Continued monitoring (ten-year plan) and peer-reviewed literature publication associated with the project should promote the advancement of the scientific 'state of the art' knowledge surrounding this pilot project. Similar floodplain restoration projects are also planned downstream of Austria in Hungary, where the formulation of restoration policies, goals and alternatives have been well analyzed before project implementation (Marchand et al. 1994; Marchand et al. 1995).

Site-specific Habitat Structures

Many site-specific habitat structures can be used as mitigation, rehabilitation and restoration tools in channelized river systems. Often these structures are needed as temporary improvements to habitat structure while long-term restoration schemes are implemented to restore habitat-forming processes (Beechie and Bolton 1999). An analysis of the design, implementation and ecological benefit of these structures is beyond the scope of the paper. Many of the techniques and structures used for site-specific bank stabilization can also be utilized for temporary structural habitat rehabilitation. The reference list provided in the Alternative Bank Protection Techniques sub-section above will provide the reader with a current list of literature pertaining to the subject.

Data Gaps: Habitat Protection and Mitigation

The aforementioned restoration techniques, projects and case studies demonstrate the existence and need for a wide range of approaches and techniques in large river restoration. The need for an interdisciplinary team for design and construction, along with community support, cannot be overstated. These projects serve as examples of the potential for lowland river restoration in different regions of the world. Many concepts similar to these have been used in Washington and the USA, but little literature has been published regarding the few projects that are in construction or have been implemented. In Washington State, several floodplain restoration projects have been completed or are in the implementation stage (e.g. Puyallup River, Pierce County; North Creek, King County, Yakima River), but little published information exists on project design, implementation, and monitoring. Thus, there is a lack of local information, both technical and conceptual, for hydrogeomorphic, floodplain, hyporheic, and perirheic habitat restoration in coarse cobble and gravel-bed rivers. While there is abundant information on the biohydrogeomorphic processes and anthropogenic alterations occurring in local gravel bed rivers (Cederholm, 1972; Cederholm and Koski 1977; Chapman and Knudsen 1980; Horner and Welch 1982; Nelson 1986; Bowles 1991; Perkins 1992; Shannon and Wilson 1993; Perkins 1993; Perkins 1994; Sedell et al. 1994; Abbe and Montgomery 1996; Wissmar 1996; Norman et al. 1998; Ritzenthaler 1998; Bradley et al. 1998; Miles 1998; Milhous et al. 1998; Dillon and Littleton 1998; Abbe 2000), little experimental information exists on their restoration. As seen above, most of the literature on lowland river and floodplain restoration has focused on fine-grained (gravel, sand, silt, clay) river channels. While this information is directly applicable to many lowland rivers here in Washington, the need for detailed local information to expand on these concepts to include other channel types (Nanson and Croke 1992) is desperately needed. This information can only be gained through the implementation of multi-scale pilot and demonstration projects that serve as experiments and learning tools in aquatic ecosystem restoration. A commitment to pre-project monitoring, design, and long-term post-monitoring will be essential for developing scientific information on the outcomes of different techniques.

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APPENDIX A

Complete Literature Database

Complete Literature Database

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