Executive Summary: Channel Design

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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.

The channel design white paper summarizes the state of current knowledge and technology pertaining to channel design methods and practices. It is based on a thorough review of published literature regarding the science of channel design. It is intended to be an overview of approaches and techniques used for channel design, and the ecological and habitat issues associated with these methods. The white paper is divided into two basic sections: one which addresses the fundamental aspects of stream channel form and process that provide a basis for channel design, and another that describes aspects of applied stream channel design methodology.

Natural stream and river systems continuously exhibit processes of adjustment that include channel migration, channel evolution, hydrologic changes, and sediment and debris alteration. An understanding of the fundamental fluvial processes is important to allow, maintain or provide for natural geomorphic processes in channel design. Streams and streamflow are defined by climatic parameters such as precipitation and temperature, as well as by physical factors such as topography, soils, geology, vegetation, and land use. Climatic and physical variability results in variability of channel form and processes. As described in the first section, it is this variability that sustains the geomorphic and ecological health and creates habitat diversity in the fluvial system. Furthermore, changes in land use impact the hydrology and sediment transport characteristics of river channels, which influence channel morphology. In the Pacific Northwest, urbanization and deforestation are two of the most common land use changes. When land use changes are known, or changes are expected, hydrologic changes can be predicted and incorporated into management decisions that include channel design.

Stream classification systems have been developed and are commonly used to characterize the physical components of stream segments and to infer other attributes. Classification systems can be a very useful tool for communicating an infinite range of changes in channel form, but they have become controversial in terms of their application to channel design given the potential limits in the systems themselves and the misapplications of the systems. The opportunities and limitations of the use of stream classification systems for both description and design are discussed in this paper.

Stream channel design is a relatively new science that is being implemented with increasing regularity by a number of varying disciplines including biologists, ecologists, geomorphologists and engineers. Objectives typically include habitat enhancement, channel restoration, channel stabilization, or various combinations. This paper addresses the establishment of design criteria as an important first step in design to facilitate mutual understanding of expectations of the property owner, project sponsor, designer, and regulatory agencies. Design criteria are expressed in relation to design discharges. A project may have a number of design discharges pertaining to different levels of conveyance and performance issues of channel banks, channel bed, and habitat structures. Varying levels of risk tolerance associated with design discharge are often governed by the physical conditions of the project, ranging from a completely natural setting to a confined urban setting.

Hydraulic analysis provides the foundation of river restoration design and is the basis for further analyses such as sediment transport and conveyance. The use of one-dimensional hydraulic models is widely accepted and used for a range of applications such as flood stage analysis, tractive force analysis, and for inputs to sediment transport analysis. Sediment transport analysis is one of the most important components in channel design but is far less often evaluated. Sediment transport analysis focuses on channel stability by evaluating the conditions of equilibrium where the amount of sediment coming in is equal to the amount of sediment going out. Various sediment transport models exist, but their applicability as a design tool is largely dependent on the particle sizes they were calibrated with. Sediment transport is currently an important component of fluvial geomorphic and hydraulic research, and should eventually become a routine part of channel design.

Three common approaches to channel design analysis are described in the white paper; these include: the reference reach approach, the empirical approach, and the analytical approach. The first two approaches are the simplest, but do have certain limitations, such as: 1) the assumption that a design reach is under regime, or is stable; and 2) applicability to the conditions under which specific relationships were calibrated. An analytical approach is desirable as channel conditions are quantified through analysis rather than assumed; however, it is not regularly applied due to the level of data and time needed, and the level of experience in the designer.

Within the context of this white paper, design issues and ecological considerations for measures to increase habitat complexity and channel stability are described. These have been sorted into four general categories of stream channel modifications: 1) channel bed and longitudinal profile; 2) channel planform; 3) channel cross-section; and 4) creation or adjustment of high flow channels. The success and failure of various techniques reported in the literature are described within the framework of these categories. Channel design within the urban environment is also discussed, with particular attention to design approach within the constraints of the altered channel form and function.

Lastly, an outline is proposed for the development of a channel design guidance document.

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Contents

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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.

Fundamental Aspects of Stream Channel Form and Behavior

Geomorphic Processes and River Habitat

Streams are the arterial system of the land. The stream continuum begins with the smallest stream and ends at the ocean. Streams form a continuum of physical environments and associated aquatic and terrestrial plant and animal communities (Vannote et al. 1980). This continuum is a longitudinally connected part of the ecosystem in which downstream processes are linked to upstream processes. The characteristics of streams and streamflow in a particular watershed are defined by climatic parameters such as precipitation and temperature, as well as by physical factors such as topography, soils, geology, vegetation, and land use. The watershed provides two primary inputs that control channel form – water and sediment. These inputs ultimately drive fluvial processes and largely determine the nature of channel systems and channel process.

Plants and animals have adapted to several distinct habitats that are characteristic of river corridors. These habitats can be subdivided into benthic, aquatic, and terrestrial zones (MacBroom 1998). The benthic zone consists of the streambed. Biota associated with the benthic zone are generally attached to or buried under the channel bed substrate. The aquatic zone is characterized by flowing water, and is associated with animals such as fish, amphibians, and aquatic plants. Adjacent uplands make up the terrestrial zone, which is occupied by plants and animals that live on land that is rarely submerged for long periods of time.

The River Continuum

The River Continuum Concept proposed by Vannote et al. (1980) describes riverine biological processes in terms of organic matter flux, including its sources, movement, storage, and consumption. Based on these processes, rivers can be described in terms of three basic ecosystems, which correspond to primary ecological processes in small, medium, and large streams. These three primary ecosystems are distinguished by the sources from which biota derive energy, including detritus, photosynthesis, and sediment. The concept translates the energy equilibrium theory from the physical system of geomorphologists into a biological analog. In the first of these ecosystems, small streams receive organic material directly from the terrestrial zone through leaf fall and woody debris. Within medium sized streams, aquatic plant growth contributes substantial organic matter. In large streams, organic matter is derived primarily from sediment sources.

Riverine ecology is inextricably linked to the physical processes that control river form and behavior. As described by the River Continuum Concept, producer and consumer communities characteristic of a given reach river reflect the means by which the river system expends its kinetic energy toward achieving a state of dynamic equilibrium. Therefore, over extended river reaches, biological communities that approach equilibrium with the dynamic physical conditions of the channel should become established (Vannote et al. 1980).

The Influence of Geomorphic Processes on Habitat Quality

Fundamental fluvial processes include the downstream conveyance of water, sediment, nutrients, and organic matter. River geomorphology is also strongly affected by vegetation and geotechnical characteristics of channel boundary materials. The combination of factors associated with hydrology, climate, sediment transport, riparian vegetation, and boundary materials ultimately determines river channel form and process. The range of geomorphic processes that result include sediment entrainment, sediment deposition, floodplain inundation, recruitment of large woody debris, and creation and maintenance of riparian and aquatic habitat.

Aquatic habitat is a product of fluvial processes, and diversity is a key component of productive stream habitat (Hill et al. 1991, Gore 1985, Poff et al. 1997). While geomorphologists may speak of channel forming flows in a relatively mechanical sense, biologists may view flow events in terms of their effects on aquatic habitat. Hydraulic forces differ both on a reach scale, locally (such as in the vicinity of a boulder or submerged log), and over the range of flows that a stream experiences. These forces create scour pools and transport, sort, and deposit coarse and fine bed materials, thus creating a diversity of bed forms and local substrate sizes (Lisle 1981). The resulting variety of depths, velocities, substrate types, and cover meets the needs of the various life stages of fish and other aquatic organisms (Gore 1985).

Larger-scale geomorphic processes such as channel migration, formation, and abandonment also play important roles in habitat formation. Abandoned channel reaches often become backwater areas, ponds, wetlands, and high-flow channels. These off-channel areas provide a variety of habitat conditions exploited by aquatic and terrestrial organisms.

Variability occurs on a temporal scale as well. Booth and Jackson (1997) note that anadromous salmonids “depend on particular combination of water and sediment fluxes to maintain favorable channel conditions.” Most pacific northwest aquatic organisms have evolved within dynamic stream systems, in which pools, bars, and other habitat features are continually reworked and reformed. Such temporal variability through disturbance is an important characteristic of their aquatic habitat.

Actions that disrupt natural fluvial processes can rapidly alter benthic, aquatic, and riparian habitat. Although sediment, hydrology, vegetation, and channel boundary materials combine to generate quality habitat in natural river settings, a wide spectrum exists both in fluvial conditions and the level of biological function they provide. This spectrum extends from pristine conditions, where geomorphic equilibrium can be achieved, to severely impacted urban settings, where fundamental fluvial processes are highly disrupted. Due to the extent of impacts on many systems, such as channelized urban streams, significant challenges and limitations may exist with respect to development, maintenance, or enhancement of habitat.

The Basics of Channel Form: Slope, Pattern, and Boundary Material

Channel Slope

Channel slope, or gradient, is the amount of vertical drop per unit of horizontal distance along a stream. The amount of energy available for sediment transport is directly related to slope – a steeper gradient gives a stream more energy to move larger particles, such as boulders. Although stream energy is not solely based on channel gradient (other factors such as channel geometry and hydraulic roughness are important), slope is a key factor in determining the channel's erosive capacity. Channel slope is closely related to a stream's position in the watershed, with slope decreasing in a downstream direction .

Recent work focusing on steep channels has revealed a number of distinctions of fluvial form and process between steep, headwater streams in mountain environments and those in lowland channels (e.g., Jarrett 1990, Grant and Swanson 1995, Montgomery and Buffington 1997). For example, steep channels commonly have narrow and discontinuous floodplains (Lisle 1987), in contrast to lowland systems in which these channel forms are common. Defined as the area adjacent to the active channel, separated from it by banks, and built of materials deposited under the present flow regime of the river (Wolman and Leopold 1957, Graf 1988), floodplains are usually replaced by valley walls in steep stream systems (Grant et al. 1990). Furthermore, hillslope processes such as debris flows and landslides occur commonly in steep channel environments, delivering material that resists transport for long periods of time (Lisle 1987, Grant and Swanson 1995). Lowland streams, on the other hand, are separated from hillslopes by floodplains and terraces, lessening the impacts of hillslope processes on the channel. Finally, the hydraulics of high-gradient streams are influenced by large boulders, which may have diameters on the same scale as channel depth or width, creating large-scale roughness elements on the channel bed. These roughness elements cause large energy losses and disrupt velocity profiles, complicating hydraulic processes in steep channels (Bathurst 1978, Jarrett 1985).

Channel Form and Pattern

A variety of channel bedforms and patterns are found in natural river and stream channels, and are therefore emulated in channel design. Predominant bedforms in alluvial and bedrock channels include channel bars, riffle-pool sequences, and step-pool sequences. The predominant natural alluvial channel patterns are meandering and braided, although high-gradient mountain streams often have straight patterns through narrow valley walls or bedrock. Other important factors that affect channel form are the growth of riparian vegetation along the channel banks or floodplain, and the presence of large woody debris in the channel, both of which are discussed in a later section.

Channel Bars

In both meandering and braided streams, channel bars are ubiquitous features representing sediment deposition and storage in the channel. Bar formation is undisputedly a result of local reductions in sediment transport capacity. Bars are present in sand- and gravel-bed streams, and occur on the inside of bends (point bars), along channel margins, and within the active channel flow. Channel bar terminology includes a substantial and inconsistent array of names that has not yet been standardized in the literature (Smith 1978). Channel bars that divide channels and divert flow are responsible for the initiation and maintenance of the braided channel pattern (Ashmore 1982).

Riffle-Pool Sequences

Riffles and pools are often the dominant bedforms in coarse-grained channels. In alluvial channels, pools are created by erosional processes on the outer part of river bends, and below in-stream obstructions. Riffles are associated with straighter, often higher-gradient, areas and are characterized by shallow, faster flow. The spacing between pools and riffles is often remarkably consistent across a range of scales. Leopold et al. (1964) determined that riffle spacings were consistently on the order of five to seven times the channel width. More recent research, however, suggests that spacing on some streams may be only one to four times the channel width (Rinaldi and Johnson 1997). Riffle-pool sequences are also found in bedrock channels, often in association with low-flow channel morphology in which the pools and riffles have established in the thin veneer of channel bottom alluvium (O'Connor et al. 1986).

Step-Pool Sequences

In bedrock or high-gradient channels, pool-riffle sequences are replaced by step-pool sequences. Pools are associated with channel-wide steps, which are short falls perpendicular to the channel axis that separate a backwater pool upstream from a plunge pool downstream (Grant et al. 1990). Step-pool sequences (also called steps or stepped-bed morphology) are especially common in steep, mountain headwater streams where the size of bed materials is large relative to the channel size (Chin 1989). Step-pool units are composed of cobbles, boulders, bedrock, and/or large woody debris arranged perpendicularly or obliquely to the channel (Wohl 1998), with pools usually spaced one to four channel widths apart (Chin 1989, Grant et al. 1990). The relatively close spacing of steps creates highly turbulent flow and continuous energy dissipation, allowing step-pool systems to remain stable in high gradient settings. Step-pool channel morphology is generally formed by high magnitude, low frequency flood events, and may therefore be stable for long periods of time during low flows (Chin 1989). Montgomery and Buffington (1997) provide a thorough review of the morphology and processes associated with step-pool channels.

Channel Patterns

Channel pattern describes the planform of rivers and streams, and includes those that are straight, meandering, and braided (Leopold and Wolman 1957). Channel and valley width, boundary materials, slope, and riparian vegetation all tend to influence channel patterns, which form a continuum in response to varying energy conditions ranging from single-thread (straight, meandering) to multi-thread forms (braided) (Richards 1982).

The assessment and identification of geomorphically stable channels has largely concentrated on single-thread, meandering stream systems. The high rate of change with braided systems through channels shifting has generally resulted in the assumption that multi-channeled systems are inherently unstable, and as such, restoration of these systems should concentrate on formation of a single-thread channel. As early as 1957, however, braided channels were identified as a dynamically stable planform (Leopold and Wolman 1957). As these systems generally display a high degree of sediment mobility, it can be intuitively difficult to assess the degree of sediment transport continuity. Research has shown that over 30 years on the extensively braided Brahmaputra River in Bangladesh, there was no significant change in river stage even though an estimated 15 billion tons of sediment had been transported through the system during that time frame (Halcrow 1992). Thus, it may be difficult to recognize braided streams as stable since they often undergo rapid channel change due to the high mobility of bed and bank sediments (Thorne 1997).

The Effect of Boundary Materials

The form of a stream channel can be fundamentally described in terms of their boundary material - materials that comprise the cross-section perimeter of the main channel. Stream lengths of similar character, termed "reaches," can be categorized as colluvial, bedrock, or alluvial, according to the composition of their boundary materials (Montgomery and Buffington 1998).

Colluvial Boundaries

Colluvial reaches are channel segments in which the boundary materials are typically deposited by off-channel processes such as mass wasting or landslides. Sediment input is largely lateral, and colluvial channels can be extremely variable through time as their form is controlled by discrete events. Colluvial reaches typically occupy headwater portions of a channel network where steep slopes are present and geologic degradation is ongoing, and they typically have high levels of woody debris input. Although colluvium typically consists of boulders, gravels and finer materials, colluvial channel beds generally consist only of larger fragments as the smaller materials are readily transported downstream. Colluvial reaches are only moderately adjustable due to the presence of materials that are too coarse for the channel to transport under most flow conditions. Schumm (1985) defined colluvial reaches as "semi-controlled" because channel movement is limited due to local controls by erosion resistant materials. By this definition, channels with extensive accumulations of woody debris can also be characterized as semi-controlled.

Bedrock Boundaries

Bedrock reaches are characterized by a perimeter of resistant rock units. Bedrock reaches exhibit little, if any, alluvial bed material or valley fill, are generally confined by valley walls, and lack floodplains. As such, bedrock channels tend to be very stable, and do not change their position through time unless relatively weak zones in the bedrock allow the channel to shift laterally or vertically. Bedrock reaches generally have steeper slopes than alluvial reaches with similar drainage areas, even though local sections of almost horizontal channel bed may occur (Tinkler and Wohl 1998). Bedrock channels evolve over geologic timescales, and thus are essentially permanent landscape features with respect to river and floodplain management. Steep headwater channels in mountain drainage basins may alternate through time between bedrock and colluvial morphologies in response to periodic sediment delivery events followed by progressive erosion of those deposits.

Alluvial Boundaries

Alluvial reaches are channel segments bounded by bed and bank materials that are transported and deposited by the stream itself. Alluvial channels are therefore free to adjust their form through erosion and deposition. Due to their high degree of adjustability, alluvial channels tend to evolve toward a state of "dynamic equilibrium," in which channel width, depth, and slope adjust to optimally convey incoming sediment and water. Where the patterns of flow and sediment influx are relatively constant, lateral channel migration is common, but channel cross-section and profile are generally maintained. Where these inputs are rapidly or severely altered, the corresponding adjustment of the channel form reflects geomorphic destabilization.

Channel Migration Zones

The delineation of an active channel migration zone (CMZ), or migration corridor, along a river course can provide insight as to typical rates of channel migration, as well as the dynamics of reaches with multiple active threads. The application of a migration corridor as a management or restoration tool can effectively minimize the application of aggressive bank protection measures at the expense of geomorphic function and habitat. The migration zone is intended to reflect a corridor of active channel migration, and can be defined temporally as well as spatially. As a result, numerous approaches have been developed for applied migration corridor delineation. These include corridor delineation by the 100-year floodplain, by geologic controls (such as bedrock outcrops or valley walls), by the distributions of soils, by planform attributes such as meander amplitude (Skidmore et al. 1999). Since no single technical procedure currently exists for migration corridor delineation, the concept has not been consistently applied in river management efforts.

Perhaps the most commonly applied means of migration corridor delineation is the application of the FEMA 100-year flood boundary. It is important to note that this boundary is defined by hydrologic inundation limits – those areas that have a one percent likelihood of inundation at any given time - and is not necessarily linked to the anticipated extent of bankline migration during any given time frame. Skidmore et al. (1999) found the 100-year floodplain of the Nooksack River in Washington to extend beyond the historic channel or meander belt width. This finding reflected the presence of low floodplain areas that extended beyond the channel migration zone. Alternatively, Pollock 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.

Hydrology: The Significance of Flow Regime in Channel Form and Process

Streamflow timing and quantity are an integral component of the geomorphic and ecological variables of river systems. River hydrology is a primary independent variable with respect to critical physiochemical characteristics of rivers, including temperature, water quality, channel geomorphology, and habitat diversity (Poff et al. 1997). The natural flow regime developed for a given watershed organizes and defines the physical structure of the environment and thus, of the habitat, which is defined largely by physical processes (Poff et al. 1997). Historically, the management of river hydrology for biological benefit has concentrated on minimum flow, however the benefits of a broad range of flows for both geomorphic and ecological function are becoming increasingly recognized (Rood and Mahoney 1990).

Primary Hydrologic Parameters

Variability in natural flow patterns is caused by watershed-scale differences in precipitation intensity, timing, and duration, as well as the effects of geology, topography, soils, and vegetation. The primary components of the natural flow regime that dictate geomorphic and ecological processes in river systems include flow magnitude, frequency, duration, timing, and rate of change (Poff and Ward 1989).

Flow Magnitude

Flow magnitude is the amount of water passing a certain point at a certain time, and is measured in terms of flux, or volume of water per unit time. Typically utilized units include cubic feet per second (cfs) or cubic meters per second (cms). Frequent, moderate high flows effectively transport sediment (Leopold et al. 1964). High flows also rejuvenate biological communities by (1) causing disturbance and channel morphology change, which are important for the health of many invertebrate and fish populations, and (2) creating open, reworked sediment surfaces for vegetation colonization. High flows mobilize sediment on the channel bed, banks, and floodplain, thus inducing channel migration, bar formation, floodplain scouring, and the formation of secondary channels that may be critical for aquatic species. These processes increase channel complexity for fish, and create new substrate for riparian vegetation colonization – both of which are critical for maintaining the long-term health of these species. In fact, the composition and relative abundance of species in a river system is often closely related to the magnitude and frequency of high flows (Schlosser 1985). Flood events are also responsible for (1) increased inputs of woody debris into forested streams, which improves fish habitat, (2) the intermittent inundation of floodplain areas, which improves floodplain productivity and diversity, and (3) the creation of floodplain wetlands, and the necessary access needed by fish to these areas.

Low flows are also important for maintaining the ecological attributes of fluvial systems, whose biological assemblages are generally adapted to natural low flow patterns. The magnitude of low flows is particularly important for riparian vegetation since plants establish on in-channel surfaces and adjacent channel banks during times of low flow in the active channel. If low flows are maintained throughout the year, either naturally or due to flow regulation, riparian vegetation may stabilize in- and near-channel surfaces, and lead to narrowing of the active channel (Friedman et al. 1996). Thus, both consistent instream flows and occasional overbank flows are required to maintain the geomorphic processes necessary for the formation of aquatic and riparian habitat (Hill et al. 1991).

Flow Frequency

The frequency of a flow refers to how often a flow above a given magnitude recurs over a given time interval. Flow frequency is defined in terms of either exceedence probability or recurrence interval. Exceedence probability refers to the chance that a given flow will equal or exceed some given value. Recurrence interval is the average interval (in years) between events equaling or exceeding a given magnitude (Dunne and Leopold 1978), and is the inverse of probability. Annual peak discharge data is used to determine flood frequency. In the U.S., prediction of extreme, unlikely peak flows (e.g., the 100-year flood event) is accomplished through the use of the log Pearson Type-III analysis (Dunne and Leopold 1978). Flow frequency values are commonly utilized to define flow magnitudes used in the development of design criteria for channel design elements (e.g., bank protection designed to withstand the 50-year flood event).

Flow Duration

Flow duration is generally assessed in terms of the percent of time per year that a given discharge is equaled or exceeded. The determination of flow duration is essential in the assessment of different flood hydrographs, as the duration of flood flows may vary dramatically in different settings. In urban areas characterized by rainfall events and impervious surfaces, floods often persist for a matter of hours to days. In contrast, in areas of snow-melt hydrology, floods may last for weeks or even months. The geomorphic effects of the different types of floods can vary dramatically with respect to sediment transport, sediment sorting, bank erosion mechanisms, and channel migration. The spatial distribution of riparian plant species is largely related to their temporal tolerance for inundation, whereas fish species distributions may be related to their tolerance of low flow conditions (Closs and Lake 1996). Therefore, the interpretation of hydrology with respect to geomorphic processes and ecological function requires an understanding of the typical duration of flood events.

Flow durations can be an important component of channel design. Any design that employs vegetation must consider the viability of those plants with respect to their anticipated inundation durations under project conditions. In addition, the design of channel cross-section must consider minimum flow depths at flow durations critical for aquatic species.

Timing of Flows

Flow timing refers to the regularity of flows, and is ecologically important because many aquatic and riparian species are adapted to seasonal hydrologic events. For example, seasonal changes in flow conditions provide environmental stimuli for fish species to instigate life cycle transitions, such as spawning, egg hatching, feeding, and migrating. Seasonal access to floodplain wetlands is also a critical factor for certain fish species (Poff et al. 1997). For many riparian tree species, such as most willows and cottonwoods, spring flooding is necessary to provide moist germination surfaces during the period of seed production and dispersal (Stromberg et al. 1991). Alterations to the timing of high flows can cause a sever decline in riparian forests, such as that which has occurred on the Missouri River since flow regulation by several dams (Reilly and Johnson 1982).

Rate of Change

The rate of flow change in a river channel reflects the slope of the rising or falling limb on a flow hydrograph, which is a plot of flow magnitude versus time. In the Pacific Northwest, rapid snowmelt during rainfall events is a dominant hydrologic process causing large flood events (Harr 1981). Such rain-on-snow events exemplify a rapid response to streamflows following precipitation, and are a major component of winter peak flows in western Washington and Oregon. Where flow duration of floods is very short, such as in many urbanized settings, the rate of change in flow magnitude is very rapid, and the hydrology is “flashy.” In contrast, in seasonal snowmelt settings, the rate of change in flow magnitude is comparatively slow, as the durations of such events are long, and flows rise and fall slowly. The rate of change can be described in terms of cfs per day, or in terms of rate of stage drop. The latter refers to the rate of change in water level over time (e.g., inches per hour stage drop). The rate of flow change in many fluvial systems has a strong influence on the success of riparian regeneration. For example, for riparian cottonwoods, the rate at which the stage drops following flooding must not exceed that of root growth in newly established plants (Mahoney and Rood 1993). Rapid reduction in stage can also have a strong impact on geomorphic processes, as exemplified by the acceleration of bank failure if the stage drops faster than the saturated banks are able to drain (Thorne 1990).

Groundwater Discharge

Groundwater can constitute a primary component of overall streamflow. In most river settings, reaches can be defined as “gaining” or “losing,” depending on whether groundwater is entering the channel, or whether the channel flow is infiltrating as groundwater. Groundwater generally is the primary source of riverine baseflow, which is the seasonal minimum flow that characterizes perennial streams. Channels that are formed and sustained predominantly by groundwater input may develop as side channels in coarse-grained alluvial systems, and these channels can generate prime incubation and rearing habitat for salmonids (Bonnell 1991). The discharge volume associated with groundwater-fed side channels has been shown to be a primary factor in the attraction of spawning chum salmon (Cowan 1991). Groundwater-fed channels located at the base of a valley wall margin or terrace margin, commonly occupying abandoned main river channel segments, have been termed “wall-base channels.” These channels often provide winter refuge and summer rearing habitat for salmon (Peterson and Reid 1984). Thus, groundwater-fed side channels are a potentially effective restoration tool in the design and enhancement of fisheries habitat (Bonnell 1991).

The Relationship Between River Flows and Primary Channel Form

Researchers have developed numerous definitions of flow conditions that have fundamental relevance to channel geometry, the most common of which are bankfull discharge, dominant discharge, and effective discharge (Knighton 1998). These flows are commonly applied in the development of channel design criteria, primarily with respect to channel conveyance and sediment transport capacity.

Bankfull Discharge

The bankfull discharge (corresponding to the bankfull depth) is often considered to be the channel-forming discharge, and has been shown to correspond to the 1- to 2-year flood recurrence interval (Wolman and Miller 1960, Williams 1978, Andrews and Nankervis 1995). Williams (1978), however, states that this frequency is an accurate measure of bankfull discharge only for approximately one third of rivers. A channel that is likely be filled to bankfull stage on average of every one or two years is large enough to accommodate runoff from the watershed during the most frequent storms. The bankfull discharge fills the channel until it just begins to overtop its banks onto the floodplain. Thus, bankfull discharges control channel morphology because they have enough stream power to erode, transport, and deposit the materials that form the banks (Riley 1998). Bankfull discharge is closely associated with "effective" discharge, which is defined as the increment of discharge that transports the largest portion of the annual sediment load over a period of years (Andrews 1980). Therefore, the range of effective discharge for transporting sediment includes the flows that construct and maintain channel form (Andrews and Nankervis 1995), promoting the bed and bank morphology used to define the bankfull condition.

Bankfull discharge is used extensively in restoration design efforts because of the prominent relationship between bankfull discharge and stable channel geometry (Hey 1997). Although bankfull discharge estimates have been used extensively in channel design, there is significant debate over the universality its estimation, frequency (1.5 to 2 years), and geomorphic function (relationship to dominant discharge). The bankfull condition is usually determined in the field according to channel and floodplain features such as cross-section topography, the presence of vegetation, and changes in sediment surfaces, and is sometimes subject to a large degree of uncertainty (Johnson and Heil 1996). In incised channels, for example, the frequency of bankfull discharge is lower due to the increased channel capacity. Williams (1978) concluded that the frequency of bankfull discharge could range from 1 to 30 years. However, Rosgen (1996b) suggested that this range of recurrence intervals resulted from an unclear distinction between elevations of the low terrace and active floodplain.

Although bankfull discharge may be directly associated with channel form in stable channel settings, its application toward channel design in unstable environments may be inappropriate due to the inherently transitional state of the channel. In such cases, the application of effective discharge as a design parameter would be more appropriate with respect to achievement of sediment transport continuity and long-term channel stability.

Effective Discharge

Effective discharge is that flow which transports the largest fraction of the sediment load over a period of years (Andrews 1980), and has been correlated to bank-full flow in stable channel settings (Andrews and Nankervis 1995). The determination of effective discharge as a design parameter can assist in the achievement of sediment transport continuity as a design objective. Sediment transport continuity is important because it is unlikely that restored channel dimensions will be stable without a balanced transport of inflowing sediment (Soar et al. 1999). A practical procedure for calculating the effective discharge for channel restoration design is presented by Thorne et al. (1999). The basic principle of this procedure is to create a bed material load-discharge histogram from the flow frequency curve and the bed material load rating curve (bed material discharge as a function of water discharge). The bed material load histogram should display a continuous distribution with a single peak. The effective discharge corresponds to the mean discharge for the peak of the histogram (Thorne et al. 1999).

Dominant Discharge

Dominant discharge is a generic term for the flow condition that controls channel form (Werrity 1997). Dominant discharge has been defined as the flow which determines channel parameters such as cross-sectional capacity (Wolman and Leopold 1957) or meander wavelength (Ackers and Charlton 1970), or as the flow which performs the most work, where work is defined in terms of sediment transport (Wolman and Miller 1960). Due to the variable means of defining the dominant, or channel-forming flow, dominant discharge has been equated with bankfull flow, effective flow, and the 1.5 to 2-year flow event. Therefore, depending on the conditions present, the dominant discharge may be equivalent to or significantly different than other, more specifically defined channel-forming flows, and often the distinction between the flow descriptors is unclear.

A comparison of channel-forming flows calculated by various means including bankfull, effective, and 2-year discharge showed that the values were very different in urban and unstable channel systems, but very similar in stable, snow-melt hydrology systems (Doyle et al. 1999b). Since restoration activities most often occur in unstable systems, the applicability of common approaches to the estimation of dominant discharge for channel design may be uncertain.

The Geomorphic Impacts of Flow Regime Alterations

Alteration of flow regimes in natural river settings disrupts the natural tendency of fluvial systems toward the development of a balanced condition of flow conveyance and sediment transport, known as geomorphic equilibrium. In fact, significant alterations in river hydrology can result in dramatic geomorphic and ecological responses throughout fluvial systems (Richter et al. 1996).

The Effects of Land Use Change

The hydrologic effects of changes in land use can result in major modifications in runoff characteristics and channel morphology (Hasfurther 1985). Land use influences runoff by changing the amount of impervious surfaces within a watershed. How fast the precipitation runs off is dependent on the percent impervious surface, the slope of the basin, and the prevalent soil type. Two of the most common land use changes that have occurred in the Pacific Northwest are deforestation and urbanization (Lyons and Beschta 1983). Both activities have had profound impacts on the hydrology and sediment transport characteristics of river channels. These activities have led to the development of “flashy” hydrographs, meaning that flood waves are of greater magnitude but of shorter duration. Even low levels of urbanization can cause increases in impervious surfaces that increase the frequency of sub-bankfull floods by a factor of 10 (Schueler 1995). The effect of these hydrologic changes is often the erosion of channel boundaries, ultimately resulting in a channel much larger than what existed prior to development (Doyle et al. 2000).

If future land use activities are known, or changes are expected, hydrologic changes can be predicted and incorporated into management decisions. Furthermore, when watershed hydrology or hydraulic models are developed, future conditions can be used to test the sensitivity of the channel morphology to land use conditions. Small changes in land use can result in rapid changes in channel morphology, particularly if a threshold is crossed. For instance, several studies on urbanization have suggested that rapid geomorphic changes occur when watershed impervious levels reach 10 to 15 percent (e.g., Moscrip and Montgomery 1997). If such a threshold is crossed, and rapid channel adjustment occurs, channel construction activities may be obliterated due to boundary erosion beyond what was expected under the previous hydrologic regime.

The Effects of Dams

The natural flow regimes of the vast majority of major inland waterways in the United States have been altered by structures such as dams and diversions. Many dams are designed to trap high winter flows and slowly release that water during dry summer months. Dams are also designed for the direct use of the impounded water for irrigation, drinking water, hydroelectric power generation, and recreation. In general, the geomorphic effect of dams is the alteration of flow patterns and the trapping of sediment. Flow regulation from dams commonly reduces the magnitude of high flows, increases the magnitude and duration of lower flows, and dramatically increases the rate of change in flows on a daily or monthly basis (Williams and Wolman 1984, Collier et al. 1996). The trapping of sediment in reservoirs results in the release of sediment-deficient water from the structure. As a result, erosion and armoring (hardening of bed with immobile, large substrate) of the channel bed downstream of dams is common (Hirsch et al. 1990). Channel incision downstream of dams may result in the lowering of base level for tributary streams and consequent downcutting of those streams, creating systemic channel destabilization (Williams and Wolman 1984). Without either high magnitude flows and an appropriate sediment supply, aquatic communities that are reliant on flooding or periodic substrate mobilization may endure increased mortality rates as a direct result of dam construction and flow regulation (Poff et al. 1997).

Altered hydrology downstream of dams can have various effects on riparian communities. Rood and Mahoney (1990) concluded that the overall reduction of downstream flows, as well as the attenuation of spring flooding, caused the collapse of riparian poplar forests on regulated rivers in the western prairies of North America. In cases where riparian communities have declined downstream of dams, the impacts are usually a result of both hydrologic and geomorphic changes. Peak flow reduction contributes to reduced channel migration, and the lack of re-worked sediment deposits required by many riparian species for colonization results in reduced plant germination. For example, alteration of the natural flow regime on the Missouri River downstream of Fort Peck Dam has been correlated to a four-fold reduction of the mean rate of channel activity for 200 km downstream of the dam (Shields et al. 2000). Conversely, controlled water releases from dams can increase the amount of riparian vegetation. Along the Colorado River in Grand Canyon, riparian habitat has increased significantly since the closure of Glen Canyon Dam in 1963. In this river system, the reduction in peak flows caused by flow regulation allowed riparian species to colonize open sandbars that were previously scoured on an annual basis (Turner and Karpiscak 1980). Similarly, along the Platte River in the central Great Plains, reduced flow magnitudes due to dams and diversions have caused an expansion of cottonwood-willow forests by increasing seedling recruitment and survival in the riverbed (Johnson 1994).

The Effects of Flow Diversions

Diversions (whether for hydroelectric power generation, agriculture, or municipal use) directly export flows from stream channels, and may completely dewater the channel downstream during certain low flow conditions. Flow diversions decrease the ability of the stream to transport sediment, and may lead to the deposition of fine sediment in gravel streambeds, a condition that is not conducive to successful fish spawning (Morris 1992). Furthermore, since streamflow is often the most important environmental factor affecting pattern and process in riparian ecosystems (Stromberg 1993, Auble et al. 1994), diversions can significantly affect riparian vegetation (Johnson et al. 1995). Such effects include a decline in reproduction of pioneer tree species along meandering rivers (Johnson 1992), expansion of vegetation and channel narrowing along braided rivers (Johnson 1994), and an increase in the spread of exotic species (Graf 1978).

The geomorphic effect of diversions is largely a function of the environmental setting. The type and magnitude of channel response to diversions has been related to the adjustability of the channels evaluated, which is a function of boundary materials, hillslope processes, hydrology, beaver dams, and large woody debris accumulations (Gordon 1995). Consequently, the effect of diversions on channel morphology is site-specific, and can range from channel narrowing and vegetative encroachment to minimal change in form or conveyance. The most significant impact of flow diversions on channel form has been shown in low to moderate gradient alluvial rivers, such as the Platte River in Nebraska. In this system, flow diversions have reduced peak flows dramatically, which has resulted in extensive narrowing and reduction of active channel threads due to vegetative colonization of the channel bed (Eschner et al. 1983, Karlinger et al. 1983).

The Geomorphic Role of Riparian Vegetation

The Influence of Riparian Vegetation on Channel Form and Process

Riparian detritus is the primary source of organic matter to headwater streams, and as such, is the basis of the food chain in river systems (MacBroom 1998). Riparian corridors provide shade and cover for both aquatic and terrestrial animals, and enhance bank stability. In addition, both riparian and upland areas contribute large woody debris (LWD) to stream channels, which increases habitat complexity and enhances sediment storage. The composition of natural riparian corridors ranges from a dominance of rigid woody species such as cottonwoods or poplars, to flexible woody species such as willows, to herbaceous species such as grasses that are low in stature and highly flexible when inundated by flow. Riparian corridors are also critical habitat for animal species that affect fluvial processes, such as beaver. The construction and maintenance of beaver dams often causes significant impacts to channel geomorphology, ranging from altering sediment storage and delivery, to alleviating flood peaks in beaver-inhabited drainages (Malanson 1993).

The influence of riparian vegetation on channel form and process has been addressed in geomorphic (e.g., Simon and Hupp 1986), hydraulic (e.g., Masterman and Thorne 1992), and geotechnical studies (e.g., Gray and Leiser 1983). Vegetation plays three important roles that affect channel form and process. First, the establishment of bar and floodplain vegetation affects channel form by influencing floodplain formation and channel narrowing, especially in semi-arid environments (Friedman et al. 1996). Second, vegetation on channel banks and floodplains increases hydraulic roughness, which in turn decreases channel conveyance and augments sedimentation (Kouwen and Unny 1973). Finally, vegetation increases the cohesion of bank sediments, thus influencing bank erosion and overall bank stability (Thorne 1990). Riparian vegetation is therefore fundamentally linked to channel pattern and shape, channel conveyance, and bank stability, making the consideration of its influence an essential component of channel design.

Vegetation and Channel Morphology

Vegetation influences channel morphology by enhancing floodplain formation, a process that has been extensively documented on semi-arid rivers. Channel narrowing and floodplain formation have followed a period of lower-than-average peak flows along rivers of the western United States during this century, and these processes appear to be directly related to the growth of riparian species (Schumm and Lichty 1963, Friedman et al. 1996). Vegetation establishes in and along the channel when the magnitude of peak flows declines, and subsequently stabilizes channel bars and floodplains. This process may be exacerbated by the introduction of exotic species, such as Tamarix (Graf 1978), or by the decrease in peak flows associated with dams (Williams and Wolman 1984).

The density of bank vegetation may also influence channel width on smaller streams. Dense bank vegetation has been associated with decreased channel width (Huang and Nanson 1997), a relationship which is especially apparent when comparing gravel-bed streams with thickly vegetated banks to streams with unvegetated banks and comparable flow magnitudes (Hey and Thorne 1986). However, riparian forests have also been linked to increased, rather than decreased, channel widths in forested basins because the shade from large trees apparently suppresses growth of shorter riparian vegetation that plays a greater role in binding bank materials (Murgatroyd and Ternan 1983).

Vegetation and Flow Conveyance

The presence of vegetation growing on a channel bed or bank influences channel hydraulics. Plant stems increase hydraulic roughness (or flow resistance), which in turn reduces the conveyance capacity of the channel and may lead to increased overbank flooding during high flows. The increase in flow resistance in stream channels lined with vegetation is dependent on vegetation density, height, and type (Kouwen and Unny 1973, Petryk and Bosmajian 1975, Kouwen and Li 1980). Unrestricted growth of dense, tall, rigid-stemmed vegetation on the channel bed and banks can lead to substantial reduction of a channel's ability to convey water. Growth of bank vegetation with flexible stems, however, leads to a much smaller increase in flow resistance and has less effect on flow conveyance. Vegetated channel banks contribute to flow resistance mainly during moderate to high flows, when banks are inundated. Such resistance promotes sedimentation, reduces bank erosion, and therefore enhances habitat.

Because the growth of bank vegetation includes the potential for reduced channel conveyance and flooding, river management strategies often include a consideration of the density and type of riparian vegetation present. Research has shown, however, that the impact of vegetative roughness on channel conveyance is related to the channel width-to-depth ratio. In fact, vegetation may only affect conveyance in channels with width-to-depth ratios of less than 12, which is less than that of most natural channels (Masterman and Thorne 1992).

Vegetation and Bank Stability

Stable river channel form is dependent on the strength of riverbank materials. On vegetated riverbanks, plants prevent mass failure by draining and drying bank substrates, and by adding tensile strength that reinforces soil. Compared to unvegetated banks, slopes covered by a stand of close-growing vegetation experience an increase in erosion resistance of between one and two orders of magnitude (Carson and Kirkby 1972). The weight of woody vegetation may enhance or reduce bank cohesion, depending on the steepness of the bank slope and the position of the tree. On steeper banks, trees may decrease bank stability. However, on gentle banks with a wide band of vegetation, the net effect is to increase stability by increasing the resistance of the bank to shear (Thorne 1990). In addition, the type of vegetation (rigid or flexible) determines its effect on bank erodibility. Rigid vegetation such as trees will locally reduce bank shear stress and erodibility, although hydraulics generated around the tree may result in local increases in shear and local bank erosion (Lawler et al. 1997). Vegetation also plays a role in bank stability by buttressing the bottom of steep banks, therefore slowing erosion caused by fluctuating river flows (Gray and MacDonald 1989). Finally, research indicates that the trapping of fine sediment around vegetation stems enhances bank accretion. Thus vegetation plays a central role in promoting sediment deposition on banks that are advancing (Thorne 1990).

Recent research by Millar (2000) focuses on the role of vegetation and bank stability in affecting channel pattern. This work concludes that the transition from a meandering to a braided channel is in part dependent on the health of riparian vegetation as it relates to the stability of channel banks. Millar's (2000) study cites the effects of streamside logging as an example of the role of vegetation removal in this pattern transition, and emphasizes that the process should be reversible. Re-establishment of vegetation and subsequent bank stabilization should return the stream to its meandering channel pattern.

The Effects of Large Woody Debris in Stream Channels

Large, or coarse, woody debris in streams consists of large roughness elements that divert flowing water and influence the scour and deposition of sediment in forested streams throughout the world. LWD influences sediment transport, geomorphic processes, and nutrient cycling (Richmond and Fausch 1995), and is important for both fish and aquatic invertebrate habitat (Ramquist 1995). The influx of woody debris into stream channels usually results from tree-fall on banks or hillslopes, and includes both riparian and upland vegetation. Processes that initiate tree-fall include wind, bank erosion, tree mortality, mass wasting, and land-use practices such as logging (Nakamura and Swanson 1993). The introduction of LWD into a stream affects channel form and process by:

- Creating steps in the longitudinal profile (thus dissipating energy in high gradient systems), forming pools and riffles, and increasing sediment storage (Nakamura and Swanson 1993, Wallace and Meyer 1995);
- Improving habitat by increasing the types and sizes of pools (Robison and Beschta 1990, Abbe and Montgomery 1996), and providing cover (Richmond and Fausch 1995);
- Forming channel bars (Malanson and Butler 1990); and
- Causing sediment deposition in channels and on floodplains that provides for riparian vegetation colonization and forest flood plain development (Fetherston et al. 1995).

In general, the effects of woody debris on stream channels vary with stream size. In low order streams, woody debris elements are large relative to the stream, and may cause channel widening and sediment storage. In high order streams where debris elements are small relative to the channel, LWD accumulations may increase channel migration and the development of secondary flow channels (Nakamura and Swanson 1993).

The effect of large woody debris in stream channels has been an area of particularly active research in fluvial geomorphology over the past decade. Descriptive studies have progressed toward more analytical research, and are summarized by Abbe et al. (1997). LWD has an important role, particularly in the Pacific Northwest, for providing channel variability as well as in-channel habitat for fisheries resources. In many systems, LWD is a critical component of channel complexity, and may be a governing factor controlling channel morphology (Montgomery et al. 1996, Rice and Church 1996). Woody debris jams play a major role in sediment transport dynamics, as water and sediment stored behind jams can be rapidly released, creating transport events ranging from small sediment pulses to high magnitude debris flows and floods. Woody debris has been identified as a potential threat to recreational safety, infrastructure stability, and flow conveyance, and its application in design has been highly scrutinized as a result. Ongoing disagreements regarding LWD emplacements range from its fundamental acceptance as a viable restoration procedure, to the determination of appropriate implementation procedures – for example, whether to use loose wood, which may threaten infrastructure, or cabled wood, which may create recreational hazards.

While LWD has been used in channel restoration efforts for many years, it has been applied somewhat indiscriminately, with little discretion or analysis (Shields 1996). Recently, LWD has been analyzed as a hydraulic feature of river channels (Wallerstein and Thorne 1996, Abbe et al. 1997). These studies provide the foundation from which to approach channel designs utilizing LWD. However, in many stream systems where woody debris may not be natural to the system, its incorporation into design strategies may be inappropriate.

The Use of Stream Classification in Describing Form and Process

The high degree of natural variability in the morphological and functional characteristics of stream channels reflects a broad continuum of form and process that can be difficult to divide into discrete segments. In order to impose some degree of order on the broad spectrum of form and behavior, stream classification systems have been developed in which streams are grouped into categories based on objective criteria. Classification systems are commonly used to characterize the physical components of stream segments and to infer other attributes. At times, these classification systems are also used in the design process. Channel classification has been utilized to achieve the following:

- To facilitate communication;
- To predict channel response to land use or environmental change (Montgomery and Buffington 1998);

- To define a probable end state for the fluvial system and methods of restoration which will be in line with this end state (Kondolf 1995);
- To derive dimensionless ratios among common physical channel attributes (Rosgen 1994);
- To evaluate the potential effects of projects that will alter channel characteristics; and
- To develop data collection strategies.

The Development of Classification Systems

Stream classification systems are largely based on geomorphic parameters of channel form, such as size, shape, pattern, boundary materials, sediment characteristics, and drainage pattern. Classification of rivers is by no means a recent endeavor; the multitude of classifications that have been developed span an entire century of research into fluvial systems. Well-known classification systems include those of Davis (1899), Leopold and Wolman (1957), Schumm (1977), Palmer (1976), Brice (1982), Frissell et al. (1986), and Rosgen (1994). Some older classifications, such as the stream order classification first proposed by Horton (1945), are still widely applied, although others, such as W.M. Davis' geographic cycle, are largely dismissed by modern geomorphologists (Doyle et al. 1999).

Morphology-Based Channel Classification

The use of channel typing as a primary means of describing basic channel form is an accepted practice among river scientists, with various classifications currently used as common vocabulary within the discipline. These classification-based channel descriptions include those related to:

- Channel patterns, such as braided, meandering, and straight (Leopold and Wolman 1957, Brice 1975);
- Sediment load, such as bed load, mixed load, and suspended load (Schumm 1977);
- Boundary material, such as alluvial, colluvial, or bedrock (Gilbert 1914, Schumm 1977, Montgomery and Buffington 1998);
- Stream order (Horton 1945, Strahler 1964); and
- Drainage pattern, such as dendritic or radial (Howard 1967).

Although the application of channel classification as a descriptive tool is widely accepted, the translation of the basic classification of channel form into a prescription for channel design is of significant discussion amongst river scientists and engineers. One of the more popular, and at times controversial (Miller and Ritter 1996, Rosgen 1996a), classification systems currently used is that developed by Rosgen (1994, 1996b). The Rosgen classification has seven primary categories for streams based on degree of entrenchment, gradient, width/depth ratio, and sinuosity. Each of these categories has 6 subcategories that are defined in terms of bed and bank materials. While Rosgen's scheme has a high degree of utility and acceptance with respect to general communication of channel form, it does not consider the processes that govern, or are the causal factors, of channel form. The response potentials associated with the classification lack scientific rationale in terms of governing physical processes (Montgomery and Buffington 1998). Therefore, its use as an actual design tool is problematic (Miller and Ritter 1996). Furthermore, some of Rosgen's classification parameters have proven to be inaccurate outside of the area in which the classification was developed, suggesting that the Rosgen scheme may only be regionally applicable (Rinaldi and Johnson 1997).

Process-Based Channel Classification

The limitations of the Rosgen classification system with respect to channel design exemplify a major problem of all classifications that are based on existing channel morphology – the failure to account for dynamic adjustment or evolution of the fluvial system (Thorne 1997). As a result, there has been an effort to base stream categorization on adjustment processes and trends of channel change rather than existing morphology (Montgomery and Buffington 1998). These process-based classifications are fundamentally different from morphology-based approaches, in that they require an assessment of the ongoing nature of channel adjustment. Commonly, this requires an inference of channel adjustments via channel form, which depends in large part on the judgment and experience of the assessor. The assessment of ongoing channel adjustment requires careful observation and a high level of understanding of the linkages between river form and process (Thorne 1997).

The Application of Classification in Channel Design

Classification can be a very useful tool for communication, providing order to a seemingly infinite range of manifestations of channel form. However, the process of fitting natural streams into a classification system should not be mistaken for the process of understanding stream behavior and form (Doyle et al. 1999). In terms of utilizing morphology-based classification schemes in channel design, there is an inherent risk that channel types desired for aesthetic value will be designed without a full understanding of the geomorphic processes at work. For example, Ashmore (1999) demonstrates that a focus on stream type as a primary variable under-represents the importance of sediment grain size and slope. Other studies identify the crucial need to perform channel assessments beyond a local reach-based scale, such that watershed-level controls are understood. On the reach level, site-specific studies of channel dynamics, including a historical channel analysis, are essential prior to restoration design (Kondolf and Larson 1995).

It is clear that a fundamental understanding of channel dynamics on both temporal and spatial scales is critical for the long-term success of channel design efforts. Classification systems tend to be influenced by the classifier's discipline, or more importantly, their geographic region of experience. Hence, it is critical to be familiar with the region wherein a classification system was developed in order to determine its applicability to the project of interest. The development of process-based classifications may facilitate the use of classification in channel design, however even this improvement will not circumvent the need for a fundamental understanding of the linkage between river form and process.

Assessing Channel Processes: Geomorphic Evolution and Stability

It is important to understand the fluvial geomorphic character of a stream reach or watershed prior to the alteration of channel attributes in the system (Kondolf and Larson 1995). The determination of whether or not the channel segment of interest is in a condition of equilibrium or disequilibrium can be used to define the most appropriate approach to effective channel design. One of the most basic concepts in fluvial geomorphology is that stream channels tend toward an equilibrium state in which the input of mass and energy to a specific system equals the outputs from the same system (Graf 1988). A corollary to this condition is that the internal forms of the system (such as channel morphology) do not change in the transfer of mass and energy. Thus, stream channel equilibrium generally refers to the relative stability of the channel system. The terms "stable" and "unstable" are often used to describe fluvial systems in equilibrium or disequilibrium. The characterization of stability or instability is best achieved through geomorphic assessment, which is based on an understanding of the geomorphic evolution of the channel, as well as of sediment transport dynamics.

The Assessment of Geomorphic Evolution

For channel design, identifiable trends in past, present, and future geomorphic conditions should be assessed. Historical analysis can help define fundamental evolutionary aspects of the river, including channel form, hydrology, sediment regime, natural disturbance regime, and land use changes that have directly influenced the channel (Kondolf 1995). Historical analysis can provide insight as to watershed level alterations, such as urbanization rates and patterns, as well as channel engineering works, such as channelization (Newson et al. 1997). The fundamental understanding of geomorphic channel evolution has been identified as an optimal means for evaluating the physical and ecological potential of the channel (Kondolf and Larson 1995).

It is important to note, however, that historic channel conditions commonly provide inappropriate templates for channel design due to the cumulative impacts of alterations on channel form and process. For example, rapid changes in land use, such as urbanization, can dramatically affect hydrology and sediment supply, and therefore stable channel configuration. Such changes may require the estimation of current or future conditions of hydrology and sediment transport. Thus, although a fundamental understanding of channel and watershed history is critical for the assessment of current channel form and process, the replication of that historic channel form may be inappropriate under existing conditions or projected future conditions.

Defining and Assessing Channel Stability

The status of geomorphic stability for a given channel may be described as unstable, dynamically stable, or stable and moribund (Thorne et al. 1996). Unstable conditions reflect relatively rapid ongoing adjustments of pattern, cross-section, or profile. All river channels are dynamic by nature, continually adjusting to independent variables of hydrology (climate, runoff) and geologic conditions (topography, sediment yield) within a given watershed. Long-term adjustments are typical, and mild states of geomorphic disequilibrium are common. However, where independent variables are rapidly altered, the rate of channel adjustment can be so rapid that the ecological balance is disrupted and effective resource management is significantly complicated. These rapidly adjusting channels are generally considered “unstable” with respect to channel design.

Stable channels convey inflowing sediment at the same rate that it is delivered to the system, and maintain their general form and pattern over the time frame of centuries. Stable channels can be distinguished in terms of their ability to adjust to changing inputs as either dynamically stable or moribund (Thorne et al. 1996). Dynamically stable channels are alluvial and adjustable in nature, such that any change in inputs results in channel response and destabilization. These stable channels maintain their general form and pattern, although their stable condition does not preclude lateral migration and associated dynamics such as bank erosion and sediment deposition. The resiliency of these channels to changing inputs is limited, and the potential for destabilization is significant. Moribund channels are not strictly alluvial in nature, and their ability to adjust to current conditions is limited. Usually, these channels were formed under conditions of higher energy and sediment supply. Moribund channels are less prone to systemic destabilization as a result of human impacts. Because these channels lack sufficient energy or sediment inputs to naturally recover from disturbance, direct impacts such as cross-section modification may significantly affect both their form and ecological attributes.

Numerous methodologies have been developed for the assessment of channel stability. These assessment procedures may include or emphasize different geomorphic parameters, such as qualitative descriptors of bed and bank conditions (Pfankuch 1978), the status of incised channel evolution (Simon and Downs 1995), hydraulic geometry (Thorne et al. 1996), stream classification (Myers and Swanson 1992), or sediment mobility (Johnson et al. 1999). Reviews of various assessment measures can be found in Johnson et al. (1999), Shields and Doyle (1999), and Doyle et al. (2000). The assessment procedures commonly require the application of a rating for a given condition, and summation of rankings to determine relative stability (e.g., Johnson et al. 1999). It is critical at an early point in management policies to determine the parameters that will be used to define changes in channel conditions. Values based on bankfull discharge, slope, and bed material size have all been used to define channel stability, and thus would be appropriate for channel parameters defining channel change (Johnson et al. 1999).

River managers must consider acceptable levels of change for various river systems, and whether or not changes outside of these levels warrant remedial measures (Doyle and Harbor 2001). One way of developing a baseline approach for levels of acceptable change is to examine historical rates of change for a channel within a watershed. Given the temporal and spatial frames of change based on this analysis (e.g., average of 20 feet of lateral bank erosion per 5 years), managers can establish policy to address rates of change beyond this acceptable level. For instance, if lateral migration is twice that of normal historical rates, then strategy X will be employed. If migration is four times that of normal historical rates, then strategy Y, being more costly and aggressive that strategy X, will be employed. Regardless of the case, decisions should be made based on the underlying acceptance of the fact that river channels will naturally change their morphology, and that certain levels of this adjustment within an entire watershed must be tolerated.

Assessing Channel Processes: Sediment Transport Dynamics

The caliber, volume, and transport dynamics of sediment exerts a major control on channel form and geomorphic processes that create and sustain aquatic habitat in all river systems. Sediment caliber dictates what geomorphic features and associated habitat types (e.g., sand bed vs. gravel bed) will be characteristic of a given channel. Sediment volume can affect the stability of a channel, causing channel aggradation if the volume delivered is in excess of the transport energy available, and causing channel degradation if the volume is insufficient. Sediment volume may also affect channel pattern and slope, with high volumes of coarse sediment resulting in steep slopes, high width/depth ratios, and braided channel patterns (Schumm 1977).

Some degree of sediment mobility is critical for the ecological health of a river system. Habitat is created and sustained through processes such as the maintenance of pools and riffles, the formation of transient bars, the deposition of spawning gravels, and the flushing of fines from bed substrate. Pools and riffles provide areas for fish to feed, breed, and find cover. Pools tend to scour at high flow and fill at low flow, whereas riffles may scour at low flow and fill at high flow (Keller 1978). Sediment sorting through selective transport creates quality habitat for benthic organisms, which in turn are food for aquatic species such as fish. The maintenance of pool-riffle sequence morphologies and the effective sorting of bed materials exemplify balanced conditions of sediment caliber and transport energy that serve to generate and maintain quality aquatic habitat.

Channel design for geomorphic stability requires that the sediment delivery to the project reach be in balance with the transport capacity of the reach. Thus, the direct assessment of sediment transport conditions can lend significant credibility to design efforts.

The Type of Sediment in Transport

The sediment cycle begins with the erosion of soil and rock in a watershed and transport of that material by surface runoff. The transport of sediment through a river system to the ocean consists of multiple erosional and depositional cycles, as well as progressive physical breakdown of the material. Many sediment particles are intermittently stored in alluvial deposits along the channel margin or floodplain, and ultimately re-entrained via bank and bed erosion. Total sediment loads consist of suspended load (the fine-grained fraction transported in the water column) and bedload (the coarse-grained fraction transported along the channel bed).

Sediment transport evaluations generally begin with a determination of the size fractions of sediment present within a given reach of channel. The measurement of sediment caliber can be performed by several means, many of which are reviewed by Church et al. (1987). These methods include pebble counts, sieve analyses, or suspended sediment measurements. The most commonly used method of sampling coarse riverbed material is that developed by Wolman (1954). Despite the development of more sophisticated statistical techniques for bed material analysis (Rice and Church 1996), the pebble count method remains widely used due to its simplicity and almost universal acceptance. Pebble counts are based on analysis of the relative area covered by given sizes, and essentially consist of measuring the intermediate axis of 100 clasts collected either at random or within a grid.

In cases where the dominant bed material is sand or finer, sieve analysis is necessary. Sieve analysis is conducted on bulk samples taken from the field (Church et al. 1987), and consists of sifting sediment through several standard sized sieves. The amount of sediment remaining on each sieve is then weighed to determine the percent of the total weight of a given size fraction. When the material is finer yet, suspended sediment measurements are necessary. Suspended sediment measurement is usually done by pipette analysis (Boggs 1987). Sediment sampling allows for estimation of size gradations in motion at given flows and provides useful information on design elements relative to substrate size.

The Mobility of Bed Sediment

The assessment of sediment mobility within a channel requires an understanding of the sediment size gradation present, as well as the transport energy available to mobilize that gradation. In many cases, the evaluation of the transport energy available to transport the size fraction present is deemed sufficient for channel design (Newbury and Gaboury 1993). This is referred to as "incipient mobility", and addresses mobility purely in terms of sediment size mobilized, rather than sediment volume mobilized. In more complex cases, however, such as those in which the incoming sediment volumes are either excessively large or small, the more difficult calculation of transport volumes may be necessary. Sediment volume is typically represented by stream power, which represents the force needed to transport sediment in a channel. Stream power is a representation of channel capacity, or the quantity of material that the flow is able to transport. A thorough review of various stream power equations is provided by Rhoades (1987).

The coarse fraction of a given sediment gradation is generally not in motion under low flow conditions. As flow increases, the energy imparted on sediment increases until at some point, the particle is mobilized. The point at which a sediment particle is just set into motion is referred to as incipient motion, and the shear stress at incipient motion is called the critical shear stress.

Shear stress is a measure of the erosive force acting on the channel boundary, with the force acting parallel to the area. In a channel, shear stress is created by water flowing parallel to the boundaries of the channel. Shear stress can be divided into bed shear and bank shear. Bank shear can be determined by multiplying the bed shear value by a coefficient from Lane (1955). Maximum bank shear, based on a trapezoidal channel, is 0.75 times the bed shear at a distance 1/3 up from the channel bed. Different channel shapes and bends will also affect the values for bank shear.

Shear stress calculations determine the force of the water on the channel particles. By knowing the amount of shear stress in a stream, the particle size necessary to withstand these forces can be found. This is important when designing a channel to withstand a certain design flow or flood flow. Shear is calculated by the equation,

$$\tau = \gamma h s$$

where τ is the shear stress, γ is the specific weight of water, h is the water depth, and s is the slope of the channel. The specific weight of water is inversely related to water temperature. The water depth is a function of flow magnitude and channel geometry. Shear stress will therefore be greatest in steep streams during high flows.

Critical shear is the shear stress required to mobilize sediment of a particular grain size. In order to calculate critical shear stress, the Shields equation is used:

$$\tau_c = \tau_c^*(\gamma_s - \gamma)D$$

where τ_c^* is the dimensionless Shields parameter for entrainment of a sediment particle of size D, and γ_s and γ are the unit weight of sediment and water, respectively (Graf 1988). Generally, the parameter D is taken to be D_{50}, the median grain size of the bed sediment. The Shields parameter is dependent on particle size and packing, and may range from 0.1 for loosely packed gravel to 0.01 for imbricated deposits (Johnson et al. 1999). Incipient mobility of stream sediments has been actively researched for over 80 years, and a summary of this research can be found in Buffington and Montgomery (1997). Their work suggests that the lack of universal Shields parameter values warrants great care in selecting those values in mobility assessments.

In incipient mobility assessments, the critical shear value is generally calculated using the D_{50} of the sediment gradation present (Chang 1988). Sediment mobility has been described in terms of shear stress ratio, which is the ratio of the shear stress present to the critical shear required to mobilize the D_{50}. Wilcock and MacArdell (1993) estimated that a shear stress ratio of 2 is needed to mobilize the entire bed of a channel. Channel stability was defined by a bankfull shear stress ratio of 1 in the assessment procedure developed by Johnson et al. (1999). This implies that under conditions of sediment transport equilibrium, the median grain size is at incipient mobility at bankfull discharge. Furthermore, at a bankfull shear stress ratio of greater than one, the channel is likely to degrade; if the ratio is less than one, transport is limited and aggradation is likely.

It is important to note that the movement of sediment in fluvial systems tends to move in a series of slugs, pulses, or waves (Graf 1988). For example, in a study on the East Fork River in Wyoming, Meade (1985) concluded that sediment moved in three pulses over a one-year period. The movement of each pulse was correlated with the pulse of water discharge resulting from snowmelt. This study also suggested that sediment is transported downstream in a series of waves; when discharge increases, material stored in pools moves to the next pool downstream. Such wave-like or pulse-like movement is typical of semi-arid streams, though it may be less common in humid environments (Graf 1988).

Typical Processes of Channel Destabilization and Natural Recovery

The assessment of channel stability can be achieved through an understanding of linkages between channel form and process. With respect to time scales generally applied in channel design (engineering time frames), channel stability can be described in terms of the achievement of sediment transport continuity, or the ability of the channel to transport inflowing sediment at the rate which it is delivered. Under such conditions, the channel does not aggrade or degrade, and basic form and pattern are maintained. This condition generally constitutes an objective of geomorphically based channel design. However, channel designs are generally developed for unstable channel settings. Therefore, it is important to understand the typical causes of instability, geomorphic manifestations of the instability, and trends of natural recovery to an equilibrium state.

The balance between sediment supply and transport energy can be intuitively considered through Lane's (1955) relationship:

$$Q*S \alpha Q_s*D_{50}$$

Where Q is the bankfull discharge, S is the channel gradient, Qs is the bed-material discharge, and D50 is the median grain size of the sediment gradation present. Any increase in the available stream energy (stream power) will result in an increase in the caliber or volume of sediment transported. This relationship can be utilized to predict the effects of channelization, dam construction, or sediment input alterations. The primary limitation of Lane's relationship is that is does not directly predict the adjustment of channel cross-section.

It is important to note that some fluvial systems are inherently unbalanced with respect to Lane's relationship. These environments include actively developing headwater streams that represent a growing drainage network, alluvial fan environments, deltas, and tidal environments. In these settings, the achievement of sediment continuity is not appropriate with respect to longer-term fluvial processes. In most alluvial settings, however, sediment continuity can be considered as an appropriate objective in channel design.

Channel Incision

Channel incision, or downcutting, is a response to some disturbance in which there is an increase in flow energy, usually through an increase in either slope or discharge (Simon and Darby 1999). The incision process ultimately results in the development of a new channel profile at a lower elevation that has a lower slope and a regained balance with the incoming sediment load. Although the causes of channel incision are highly variable, the response of these channels follows a predictable pattern that includes a series of evolutionary stages (Schumm et al. 1984, Simon and Hupp 1986, Simon 1989). These stages typically depict a process that traces destabilization, downcutting, widening, and eventual recovery.

The process begins with an initial condition of stability, followed by a perturbation that results in increased stream energy, such as channelization or urbanization. The excess stream energy is dissipated through the degradation of the channel bed, which flattens the gradient and decreases the amount of available energy. At the same time, channel banks become higher and eventually oversteepen and fail, causing channel widening by mass wasting processes. Channel widening further reduces stream energy through cross-section adjustment. This stage is followed by aggradation along the channel margin resulting from the reduced stream energy, and riparian colonization of those surfaces. Ultimately, a new active floodplain surface is developed within the incised channel, and the pre-incision floodplain surface becomes perched as a terrace. The natural recovery of an incised channel generally requires a widening of the incised cross-section, riparian stabilization of that new cross-section, and gradient reduction by meander extension and elongation (Simon and Darby 1999).

Channel incision results from any of the following impacts (Simon 1995):

- Oversteepening as a result of channelization or meander cutoffs, dredging, base level lowering, or uplift
- An increase in discharge due to deforestation, urbanization, or transbasin diversion
- A decrease in sediment loads due to dam construction or sand and gravel extraction
- Removal of natural grade controls, such as bedrock outcrop or woody debris accumulations
- A decrease in the size of bed material (loss of erosion resistance in the channel bed)
- Flow concentration or constriction by roads, dikes, embankments, or bridges.

Incised channels are common features of disturbed landscapes. Sediment produced from incised drainages may impact local and regional water quality, and impact fish and macro-invertebrates as spawning areas are filled with sediment and water turbidity increases. Although incised channels will reach a new equilibrium state over time, the length of time for natural recovery may be unacceptable. Channel design for incised channel restoration should consider the trigger for incision – for example, in an urbanized watershed, detention facilities may be needed, whereas in an overgrazed rural setting, fencing and grazing management may be more appropriate (Shields and Doyle 1999).

Aggradation

The net accumulation of sediment within a river system reflects an excess in sediment load relative to the available transport energy. Aggradation is generally manifested in the development of mid-channel bars, loss of channel cross-section, increased frequency of overbank flooding, increased width to depth ratios, increased lateral migration rates, reduced sinuosity, increased slope, and a tendency towards braiding (Schumm 1977). Aggradational processes may also drive channel avulsion, as an aggraded channel can become perched above the surrounding floodplain.

Channel aggradation may result from the following impacts:

- Increased sediment yields from deforestation or other watershed land use change;
- Increased sediment yields due to removal of upstream blockages, such as dams, or woody debris jams;
- Increased sediment yields from mass wasting events such as landslides or debris flows;
- Loss of bank stability due to reduced vegetative reinforcement;
- Reduced discharge due to transbasin flow diversions; or
- Reduced channel slope from uplift.

Applied Stream Channel Design

Identifying and Using Design Criteria

The Lack of Standard Design Methodology for Natural Channel Design

Stream channel design is being implemented with increasing regularity, and while there have been many successful restorations documented in recent decades, the industry lacks a standard approach to restoration design. A notable exception to this is the 1999 U.S. Army Corps of Engineers manual addressing design and implementation of channel rehabilitation projects. This document represents an important first step in developing a common approach to developing a standard approach, but is not yet in common usage. There are three explanations for this lack of standardization. First, there is a wide array of hydrologic and physiographic conditions that influence design and dictate alternatives for design. For example, many bioengineering techniques for bank reconstruction can be highly successful in a short period of time in humid regions, whereas successful bioengineering is more challenging in arid regions.

Second, the random nature of hydrologic events is perceived as a factor of chance in the success or failure of channel design projects. It is impossible to predict what flows a project will experience over the years immediately following construction, and as such, it is difficult to predict the long-term success or failure of a restoration project with respect to all flows. Third, the science of river restoration is still in its creative, developmental, and experimental stage. Because of the relative youth of the science, many practitioners are still experimenting, and this situation inherently limits standardization. Related to this last explanation for lack of standardization is the fact that the science of stream channel design falls within the realm of varying disciplines including biology, ecology, geomorphology and engineering. Practitioners within these varying disciplines are generally familiar only with the components of design that fall within the realm of their discipline and training. Consequently, their "standard approach" will vary significantly from approaches adopted by practitioners from other disciplines.

The Role of Design Criteria

Approaches to channel design depend on project-specific objectives, site-specific physical conditions, the experience and background of those implementing the project, and available resources. Perceptions and goals of project stakeholders can differ dramatically. Objectives may include habitat enhancement, channel restoration, channel stabilization, or various combinations of these, or other, objectives. Physical conditions, along with resource limitations such as budget constraints, often limit channel design opportunities and dictate the options considered. An effective way to navigate the often numerous, often disparate forces molding a project is to identify and adopt project-specific design criteria. Design criteria are specific, measurable attributes of project components developed to meet objectives. Once specific design criteria have been established and agreed upon by all stakeholders, the design can proceed with a high probability of meeting shared goals and expectations, and a clear understanding of risk associated with selected criteria.

The use of design criteria may ultimately lead to standardization of channel design methods. As subsequent projects adopt and refine criteria that have been previously developed for other projects, approaches to address these criteria will likely become standardized.

Establishing Criteria for Channel Design

Design criteria can facilitate the mutual understanding of expectations of the property owner, project sponsor, designer, and regulatory agencies. Design criteria are acceptable benchmarks for individual components of a design, providing quantifiable limits of performance and tolerance for bank protection components and mitigation features. These performance limits may prescribe the mere presence of components (e.g., a requirement for the placement of a certain number of woody debris emplacements) or the requirements for reversing, preventing, or minimizing the mechanisms of failure. There are a wide variety of mechanisms of failure that should be considered as part of channel design, many of which relate to the different causes of erosion (particle entrainment, bed scour, and mass failure of stream banks are three examples).

Design criteria ensure that project objectives are fully considered during the planning and design process and that measures function over the life of a project. Design criteria provide a reference as decisions are made regarding the applicability of relocation measures, stabilization techniques, or the dimensions of particular components. Design criteria depend on the scale and extent of a particular project. Low-tech projects with little ecological effect may require only a few design criteria, whereas more complex or risky projects may require a complex suite of criteria. Design criteria make it possible to define the allowable risk associated with given design approaches. Miller and Skidmore (1998) discuss the application of hydrologic statistics to determine the level of acceptable risk associated with given design components.

Criteria should address design components associated with an entire system. Project managers must consider not only geomorphology and hydraulic engineering, but they must also consider fisheries resources, aesthetics, and cultural resources, among other interests. It is critical that designers consider the project reach within the context of the entire physical and biotic system, i.e., its place within the watershed. Channel habitat is a natural channel function and morphology. As such, in order to provide for maximum channel habitat, maximum natural function must be established in the channel morphology (Hill et al. 1991, Gore 1985, Poff et al. 1997). One component of fluvial process that may be considered as vital to meeting habitat objectives is the continued erosion and deposition of sediment within the fluvial system (Sear 1994).

At the broadest level, objectives establish what features are needed for the project to function within the physical, biological, and political setting. Specific criteria are then established to ensure that designs will provide for these needs. Criteria may be used to establish which objectives will 'trump' others. For example, in an urban setting, flood conveyance and channel stability may hold precedence over in-channel habitat. Such priorities should be explicitly stated while developing criteria for a project, as they will guide the selection of criteria and the remainder of the design efforts.

Channel design criteria may ultimately serve as a basis for measuring success of various project components. Without criteria on which designs are based, there is no way to evaluate the success of a project. The use of criteria will ultimately allow for some degree of standardization in channel design processes, and conversely, allow for diversity in objectives among varying channel design projects.

Typical Channel Design Criteria

Most channel design criteria can be related to hydrologic events, such as the 100-year flood, bankfull flow, or low flow conditions. Various project components, or objectives, will be achieved by assigning different flows to their respective design criteria. While there are no standardized criteria for channel design at this time, the application of criteria for channel design is documented by Skidmore and Boyd (1998). Design criteria for channel design commonly include vertical stability criteria, lateral stability criteria, bank stability criteria, and habitat criteria. Typical criteria established for application in streambank construction are discussed in Miller and Skidmore (1998). Bank stability criteria may be oriented toward withstanding 100-year flows, or towards being deformable under lesser flows, depending on the objective of the project. The Army Corps of Engineers recommend (1999) establishing criteria for effectiveness, environmental considerations, and economic factors for bank stabilization in the context of channel design.

Design criteria are closely associated with risk assessment. A high-risk project (a project for which failure to meet objectives would likely endanger public safety, infrastructure, or private property) would tend to require more detailed and stringent design criteria than a lower-risk project.

Under the broad-scale criteria are the more specific criteria with which engineers are more accustomed. For example, most restoration projects will need to have 2, or even 3 flow conveyance criteria: 100-yr floodplain conveyance, ~ 2-yr bankfull channel conveyance, and finally a low-flow conveyance. While most engineers are familiar with the 100-yr requirement, and most geomorphologists are familiar with the 2-yr flow, they must communicate efficiently with fisheries biologists to accurately establish the appropriate level for the low flow conveyance. In a similar vein, criteria must be established for the movement of sediment. In the area of structures such as bridges, riprap will need to be placed which will not move up to an extremely large event (e.g., 100-yr), while channel bed material may need to be mobile several times per year in order to maintain proper spawning conditions. Similarly, criteria must also be established for quantities of sediment transported into and out of the project reach.

Limitations Imposed by Design Criteria

While the development of criteria for channel design will help to ensure project success, working within the context of design criteria may reduce creative or experimental approaches to project design and implementation. While criteria serve an important function in formalizing a design framework, they should not necessarily limit opportunities or approaches. If alternative approaches are to be employed, they do not necessarily preclude use of design criteria. Rather, project designers and/or stakeholders should conduct an appropriate discussion of risk, in order to frame the context of the approach relative to more standard or more commonly accepted programs.

Analyses Used in Channel Design

Three Common Approaches to Channel Design Analysis

In general, there are three generalized approaches to channel design being implemented: the reference reach ("intuitive") approach, the empirical approach, and the analytical approach (Shields 1996, Millar and MacVicar 1998, U.S. Army Corps of Engineers 1999). Two or more of these approaches may be used concurrently, thus allowing the designer to crosscheck the results of the approaches against one another. Often, the reference reach and/or empirical approach is used to determine rough channel cross-section and planform geometry, and the analytical approach is used to verify that the chosen geometry will meet project goals for channel conveyance, stability, and sediment transport (Alexander et al. 1994, Ashfield et al. 1994).

The Reference Reach Approach

The simplest and perhaps most widely used practice of channel design analysis is based on adopting channel dimensions from stable reaches elsewhere in the watershed or from similar undisturbed reaches in the region (NRCS 1999, Shields 1996). The benefits of this approach lie primarily in its simplicity and its intuitive appeal. Often termed the 'carbon copy approach', the dimensions of a stable reach with similar drainage area are simply applied to the project reach, or are scaled based on regionally-developed regression curves which relate drainage area to channel size (Rosgen 1994 and 1998). Further, because of the ease with which this design is accomplished, data collection and design analysis is kept to a minimum, thus reducing design cost.

There are significant risks to the reference reach approach. Perhaps the most important risk is the assumption that the chosen reference reach is a stable and appropriate representation of desirable project reach geometry. Making such an assessment of the suitability of a reference reach requires a significant level of geomorphic expertise on the part of the designer (Shields and Doyle 1999). Unfortunately, this approach is often utilized by those least proficient in geomorphology or hydraulic engineering.

Furthermore, restoration projects are most often implemented on channels rendered unstable by changes in watershed characteristics such as land use, hydrology, or degree of floodway encroachment. Under these circumstances, an appropriate, stable reference reach may be difficult or impossible to find. In watersheds where channel instability is related to a change in the hydrologic regime brought on by land use, the channel "degradation" that the project seeks to remedy may in fact be the result of the channel transitioning to a stable state appropriate to the new hydrologic regime. For this reason, the reference reach approach may be ineffective when applied on urbanized watersheds, or watersheds where the hydrologic and/or sediment regimes have been altered from it historic state by agricultural or other land use practices, or flow alteration (via impoundments or irrigation withdrawal).

Empirical Design

Empirical design is design based on many observations of channels (empiricism). Empirical channel design has its roots in regime theory. Channels that are 'in regime' are those that convey the imposed water and sediment loads in a state of dynamic equilibrium, with width, depth, and slope gently varying about some long-term average (Bray 1982). Early geomorphologists studying stable, natural channels developed what have been termed 'hydraulic geometry' formulas (Leopold and Maddock 1953), which quantified channels in regime. These equations generally relate width, depth, or slope to a power relationship of dominant discharge and bed material size (e.g., Bray 1982, Parker 1982, Hey and Thorne 1986, Williams 1986).

Most of the available hydraulic geometry formulas and their range of applicability are summarized by Shields (1996). In general, these formulas are most reliable for width, less reliable for depth, and least reliable for slope Shields (1996). Exponents and coefficients for hydraulic geometry formulas are based upon more or less regional data sets, and thus authors generally recommend limiting application of a given set of hydraulic geometry relationships to channels similar to the calibration sites. Hydraulic geometry formulas are more numerous for gravel-bed rivers than for sand-bed rivers, and thus greater similarity between the project site and the calibration data should be sought for gravel-bed rivers. There are two major problems associated with using hydraulic geometry formulas to size restored channels (Shields 1996):

1. Exponents and coefficients must be based on streams with slopes, bed and bank materials, and bank vegetation similar to the one being designed. It is rare that hydraulic geometry formulas have been generated from channels of the same characteristics as those under design.

2. The formulas require the designer to select a single design discharge to represent bankfull conditions. Selection of this value in unstable systems may be arbitrary or unsubstantiated. Similarly, designers must also select a single statistic to describe bed sediment size when using hydraulic geometry relations.

It should be noted that unstable channels will vary from published relationships, and thus the empirical approach can suffer from similar disadvantages as those described earlier for the reference reach approach (Shields 1996, Rinaldi and Johnson 1997). Most notably, published empirical relationships may not be appropriate for application to channels that are in the process of adjusting to altered hydrologic and/or sediment regimes (due to urbanization, land use practices, etc.) as these channels are not in regime, and empirical relations assume regime conditions. Additionally, local or regional channel characteristics may differ significantly from published empirical relationships, even in stable channels (Rinaldi and Johnson 1997).

Analytical Approach

Analytical approaches are required when channel equilibrium is in question, and when no analog sites or empirical equations are appropriate as a consequence of changing or differing hydrologic character and sediment inputs (Skidmore et al. 2001). Further, analytical approaches are often necessary to perform details of analog and empirical design when specific design components are not addressed by analog data or empirical equations. The analytical approach often requires more data, more time, and more highly trained personnel to apply. Thus it is more popular among professional engineers with expertise in hydraulics and sediment transport (Skidmore et al. 2001).

The advantage of the analytical approach is that sediment transport and channel conditions are explicitly quantified through analysis rather than assumed (Millar and MacVicar 1998). In the reference reach and empirical approaches, the inherent assumption is that by replicating the dimensions of a stable channel, either through direct replication (reference) or through replication via hydraulic geometry relations (empirical), the designed channel will maintain sediment continuity (remain stable). In the analytical approach, some degree of sediment transport analysis of the proposed channel design is performed to better insure sediment continuity. Analytical approaches make use of hydraulic models to estimate shear stress and a variety of sediment transport functions to determine equilibrium channel conditions. As such, the reliability of analytical methods is dependent upon the confidence of hydrologic and sediment data inputs, both difficult parameters to measure and quantify accurately (Skidmore et al. 2001).

Additional Data Needs for Approaches to Channel Design

- Methods for the application of reference reach and empirical methods in strictly urbanized watersheds need to be clarified and tested.

Design Discharge

Design discharge refers to the rate of flow that a channel or floodway is designed to contain or up to which various components of channels are designed to be stable, to withstand, or to be immobile. A project may have a number of design discharges pertaining to different conveyance and performance issues (Skidmore and Boyd 1998). For example, the 2-yr discharge may be adopted as the conveyance design discharge for a channel based on the assumption that this flow approximates the effective discharge for the stream reach. In contrast, certain components of the project, such as channel banks or anchored woody debris, may be required to remain stable at a higher event, such as the 50-yr discharge (stable in this context refers to the ability to withstand the forces generated by such a rate of flow).

Channel Forming Discharge

Most channel design projects designate a channel forming, or "effective" discharge as their primary design discharge for determining channel characteristics such as channel width, depth, and slope (Millar and MacVicar 1998, Rosgen 1996a). Effective discharge is that discharge that transports the most sediment (Biedenarn et al. 1999). Thus bankfull discharge is commonly used as a surrogate for effective discharge. It is generally accepted within the industry that the 1.5- or 2-year flow (Q_2) approximates bankfull in most circumstances (Rosgen 1994). Doyle et al. (1999) suggests, however, that the 2-yr discharge is a reasonable estimate of bankfull discharge for design only under the following circumstances:

- The channel has adjusted to its current hydrologic and sediment supply regimes
- The channel is unconfined *and* alluvial.

In channels that are currently adjusting to changes in watershed conditions, have been significantly manipulated, or are confined or non-alluvial, Q_2 may not be an appropriate design discharge. In these cases it may be appropriate to adopt the effective discharge as the project bankfull discharge. Procedures for calculating the effective or "channel-forming" discharge for channel restoration design are presented by Thorne et al. (1999) and U.S. Army Corps of Engineers (1999).

Limitations in Application of Channel Forming Discharge

Non-Alluvial Channels—Non-alluvial channels are those that do not flow through relatively homogenous materials that can be eroded and transported by a stream (Montgomery and Buffington 1998). For example, streams flowing through bedrock fall into this category. As such, the relationship between bankfull discharge and channel geometry may be significantly different than typically found in an alluvial channel. Thus, it may be inappropriate to use the previously described design discharge and channel geometry relationships to design channel cross-section and planform.

Channels In Dis-equilibrium—Channels in disequilibrium (e.g., either systemically aggrading or degrading) generally do not represent conditions where bankfull discharge and channel geometry are in balance. Channels in disequilibrium include those that are either systemically aggrading or degrading, or whose beds are artificially stabilized through grade control and are laterally unstable. Such channels are generally in a state of transition (for example, incising channels typically proceed through an evolutionary sequence as described by Schumm et al. (1984) and Harvey and Watson (1986)). In these cases, bankfull discharge will not be equivalent to the effective discharge. As such, channel design should not be based on the bankfull discharge (that is, the discharge at which the banks become overtopped) of the reach in disequilibrium.

Floodway Conveyance Design Discharge

In some locations, restrictions on how projects effect floodwater elevations influence project design (Morris 1996). In these cases, a floodway conveyance design discharge (typically the 100-yr discharge) is used in conjunction with hydraulic analyses to assure that the proposed channel design meets the conveyance requirements (Morris 1996). Generally, the floodway includes the channel and adjacent floodplains.

Design Discharge for Stability of Channel Components

Application of design discharge to the stability of channel components, including banks, channel bed, and habitat structures, is becoming relatively common practice. For instance, urban municipalities often require channel components adjacent to infrastructure to be capable of withstanding hydraulic forces associated with the 100-yr discharge. The reason for establishing such design discharge(s) is to address the acceptable risk associated with the project. Risk to human safety and/or infrastructure are probably the most common reasons that conservative design discharges are applied to project components.

Hydraulic Analysis Techniques

Hydraulic Analysis and Modeling

Hydraulic analysis provides the foundation of river restoration design, particularly analytical approaches to design, as channel hydraulics are the basis for further analyses such as sediment transport and conveyance (Morris 1996). At the most basic level of analysis is Manning's equation, which simply relates channel velocity to reach characteristics such as channel slope, hydraulic radius, and an estimate of roughness (Chow 1959). There are a number of computer programs available that can be used to conduct a Manning's analysis on a cross-section by cross-section basis. HEC-RAS, which is the Windows version of HEC-2, is perhaps the most widely used and widely accepted numerical hydraulic model (Hydrologic Engineering Center 1997). HEC-RAS is a steady-state, one-dimensional hydraulic model. That is, it computes hydraulic conditions of flow for a single discharge and only calculates the hydraulics in terms of variations of depth of flow and in velocity in the downstream direction. Input for one-dimensional hydraulic models generally consists of channel cross-sections, slope, and some roughness estimates. The output of such a model is useful not only for hydraulic information such as flood stage elevations, but also as input to a sediment transport model or tractive force analysis.

A number of dynamic, multi-dimensional hydraulic models exist as well (ASCE 1998). These models are most useful in cases where local flow conditions are of critical importance (Inter-Fluve 2000). For instance, flow conditions on large rivers vary significantly across channel. As such, one-dimensional models will not accurately reflect local variations in these flow conditions (Walton et al. 1997). In such cases, particularly where local structures could be affected by river changes, it is critical to use a model of appropriate complexity. In many river restoration cases, a one-dimensional model such as HEC-RAS is appropriate.

For both hydraulic models as well as sediment transport models, the end results of the models are only as accurate as the input data and the expertise of the model user. For most models, accuracy is limited by the density of cross-section surveys and the accuracy of roughness estimates (e.g., estimates of Manning's 'n') (Burnham and Davis 1987). As such, effort should be made to ensure that the appropriate density of surveys is available and that the model is calibrated (when calibration data is available). The danger of current models is that the end results are deceptively precise, and this precision can often be mistaken as overall model accuracy. Whenever possible, both hydraulic and sediment transport models should be calibrated based on real data. Further, technical oversight/quality control of model development and interpretation of model results is incredibly valuable.

Sediment Transport Analysis

Sediment transport, along with discharge, is one of the most important, but least evaluated components of channel design. As a design component, sediment transport design focuses on providing for sediment continuity, a factor that authors unanimously cite as a condition for true channel stability (Lane 1955, Millar and MacVicar 1998, U.S. Army Corps of Engineers 1999, USDOT 1988). Channel stability in this context implies that there is no aggradation or degradation of the channel bed, or more simply, that the volume of material moving in equals the volume of material moving out (U.S. Army Corps of Engineers 1999). Most sediment transport analyses and design methods focus on channel competence, or the capacity of a channel to transport bed material of a given size. Just as important as competence, however, but less frequently addressed, is consideration of channel capacity, or the volume of sediment that a channel is capable of transporting.

Channel Competence Based Methods of Sediment Transport Analysis

Incipient motion analyses can be used to assess channel competence and to design channel components to be stable under a given discharge. USDOT (1988) and U.S. Army Corps of Engineers (1999) are useful references for utilizing tractive force (shear stress) analysis to determine incipient motion characteristics for design. Shear stress is not, however, a practical measure of tractive force in steeper channels (Bathurst 1978).

Tractive Force Analysis

Analysis of tractive force, a generalized measure of shear stress, can be used to determine channel geometry (considering primarily depth) based on the mobility of bed sediment (Shields 1996). In incipient mobility assessments, the critical shear value is generally calculated using the median grain size (D_{50}) of the sediment gradation present (Chang 1988, USDOT 1988). Sediment mobility has been described in terms of shear stress ratio, which is the ratio of the shear stress present to the critical shear required to mobilize the D_{50}. Wilcock and MacArdell

(1993) estimated that a shear stress ratio of 2 is needed to mobilize the entire bed of a channel. Channel stability was defined by a bankfull shear stress ratio of 1 in the assessment procedure developed by Johnson et al. (1999). This implies that under conditions of sediment transport equilibrium, the median grain size is at incipient mobility at bankfull discharge. Furthermore, at a bankfull shear stress ratio of greater than 1, the channel is likely to degrade, and if the ratio is less than one, transport is limited and aggradation is likely.

Because the theoretical mobile particle size is calculated, the tractive force method can be used to design a channel that is essentially rigid (non-erodible) at the design discharge (USDOT 1988). Tractive force analyses can also be used to design channel components, such as banks, to withstand the shear forces associated with a given design discharge (USDOT 1988). USDOT (1988) includes information on the calculation of shear in channel bends and on the shear resistance of various materials commonly used in channel design. Alternatively, if a mobile channel bed is desired, tractive force analysis can be applied to determine a fraction of the bed material that is mobile at a given design discharge. Two methods for addressing mobile channel beds in design are addressed below.

Mobile Channel Bed Under Fixed Slope Conditions

This approach can be applied when slope is fixed due to vertical constraints as well as lateral floodplain constraints. Analysis of moving (or 'live') beds with a known or constrained slope most often makes use of extremal hypotheses (Chang 1988). Extremal hypotheses state that a stable channel will adopt dimensions that lead to minimization and maximization of certain parameters. For instance, extremal hypotheses include the minimization of stream power, maximization of sediment transport, minimization of stream power per unit bed area, minimization of Froude number, and the maximization of friction factor. These hypotheses and their application to river design are summarized in Chang (1988). Chang (1988) combined several of the extremal hypotheses, along with standard hydraulic analysis, to generate a numerical model of flow and sediment transport, the FLUVIAL 12 model. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield channel depth and width when given discharge, slope, and bed material size.

Mobile Channel Bed Under Known Sediment Concentration

Using this approach, design will ensure that the sediment entering the reach is transported out of the reach by manipulating channel dimensions. Upstream stable channel dimensions can be used to calculate an assumed sediment supply. Channel designs will be iterated such that the channel dimensions are all capable of transporting the incoming sediment load. Because many channel dimensions will be able to do this, a family of slope-width or slope-depth relations are the end result of this type of analysis. The designer then selects any combination of channel properties that are represented by a point on the curves. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth. The hydraulic design package 'SAM' (U.S. Army Corps of Engineers 1998) performs this series of analyses for sand bed channels and is available for public use.

Limitations of Sediment Transport Analysis

Sediment size and incipient motion particle size are relatively easy to characterize from deposited bed sediments and hydraulic analysis (see the discussion of "tractive force" above). Sediment volume, however, is much more difficult to quantify. Sediment volume is typically calculated using sediment transport equations, which are notoriously inaccurate (Shields 1996, Kirchner et al. 2001). There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. As such, they are only applicable to specific types of channels.

Modeling of sediment transport remains one of the central thrusts of fluvial geomorphic and hydraulic research. It is likely that quantification of sediment volume will eventually become a routine part of channel design once the limitations of sampling and characterization are reduced. Presently, however, the scope of most project design efforts does not include an analysis of sediment transport volume, and quantifying sediment transport remains one of the greatest challenges of, and limitations to, river channel design.

Sediment Transport Equations and Models

There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. The following are suggested guidelines for choosing which of the listed existing sediment transport equations to use in any given situation. The applicability of most of the equations is related to the local bed particle size. Whenever possible, the use of measured sediment loads for testing and calibration of the chosen equation(s) is preferred (actual equations and detailed descriptions are available in standard sediment transport texts, e.g., Chang 1988):

- Meyer-Peter Muller (1948): bed material is coarser than 5 mm
- Toffaleti (1969): large sand-bed rivers
- Yang (1973): sand transport in natural rivers
- Yang (1979): sand transport when critical unit stream power at incipient motion can be neglected
- Parker (1990) or Yang (1984) gravel formulas: bed load or gravel bed rivers
- Yang (1996) modified: high-concentration flows when the wash load or concentration of fine material is high
- Ackers and White (1973) or Engelund and Hansen (1972): subcritical flow condition in the lower flow regime
- Laursen (1958): shallow rivers with fine sand or coarse silt.

In addition to the specific sediment transport equations, there are several sediment transport numerical models available for use in river engineering applications. The most common approach to sediment transport modeling is a steady-state, one-dimensional approach. That is, using channel dimensions, flow conditions, and sediment characteristics, the model performs hydraulic calculations, and then using these hydraulic characteristics, calculates sediment loads for each of the channel reaches. Based on the quantity of sediment transported for the given flow, the channel elevation (i.e., slope) is adjusted via a routing scheme. The program either performs calculations for a given range of flows, or for a given flow, the model continues until there are no more channel adjustments (i.e., equilibrium conditions). This modeling approach is the basis for the Corps of Engineers HEC-6 model (U.S. Army Corps of Engineers 1990), and is widely used. The primary limitation of this approach is that it is a one-dimensional model: no changes are allowed in the width dimension.

The next level of modeling is the semi two-dimensional modeling approach. In two-dimensional models, a similar coupled hydraulic and sediment routing scheme is used, but at the end of the routing run an estimate is made as to whether or not channel width adjustments are appropriate. Several methods are used to estimate stable channel widths: extremal hypotheses as described earlier (GSTARS 2.0, FLUVIAL 12) (Chang 1988), or bank stability estimated from stable slope angles (GSTARS 2.0, CONCEPTS) (Chang 1988). These models add a significant feature of width adjustment without adding significantly to data or analysis efforts needed. In all, these are felt to be the most appropriate approaches for most river restoration designs, particularly those projects that will involve significant modification to channel alignment, slope, or sediment loads.

The third level of modeling is the fully two-dimensional or three-dimensional modeling approaches. These models represent significant improvements in describing fluvial erosion and hydraulic processes, but this comes at a significant increase in the level of effort needed both in terms of data and analysis requirements.

Additional Data Needs for Sediment Transport Analysis

- Additional information on shear resistance of bioengineering materials and methods, including shear resistance over long flow durations and over a number of years, would aid shear-based design.

- A better understanding of the patterns of shear distribution in natural channels would greatly aid in streambank design, particularly on the outsides of channel bends.

- Simpler sediment transport modeling methods with broader ranges of application would make sediment transport analysis a more widespread component of channel design projects.

Typical Approaches to Stream Channel Design

Introduction

Channel change refers to any modification, natural or man-made, to a stream or river channel, its margins, or riparian corridor, that affect fluvial processes. Historically, human induced channel changes were intended to straighten, channelize, de-snag or dredge a river or stream to facilitate navigation and flood control (Schoof 1980). Alternatively, channel change is often the indirect result of projects with objectives unrelated to stream and river management. Human activities that alter the watershed, such as resource extraction or urbanization, can result in channel modification if steps are not taken to restore the quasi-steady situation (Kondolf and Keller 1991, Leopold 1991). The focus of this section, however, is on channel changes implemented by people to improve channel stability or aquatic habitat.

A variety of techniques are used to improve stream and river channels. Due to the often multi-faceted function of any given technique, and the variety of materials utilized in channel construction, categorization and nomenclature of techniques can vary greatly. For example, a rock grade control structure and a log sill may serve a similar function of "grade control" on an incised stream. Yet the log sill may also provide a degree of cover habitat to fish, and thus function as a habitat structure as well. Moreover, an author may group all techniques utilizing a given material type, such as woody debris, into a single category, regardless of the ultimate function(s) of the technique.

Discussion of channel design components in this section is structured to address four general categories of stream channel modification intended to:

- Modify channel bed and longitudinal profile
- Modify channel planform
- Modify channel cross-section
- Create or adjust high flow channels.

Techniques for these four categories will be discussed separately in this section. It is recognized that these characteristics are interdependent, that the categorization imposed here is subjective and is one of many ways to group and discuss channel modification techniques, and that a given technique to alter one characteristic will likely affect the others to some degree. In addition, some individual techniques may be applied to alter different characteristics.

Modifying Channel Bed and Longitudinal Profile

The channel bed profile may be adjusted by modifying the channel gradient, changing the elevation of the channel bed, or both. These adjustments may be carried out for the following reasons:

- To provide complexity and diversity of habitat
- To provide channel stabilization (either bed or bank)
- To reconnect the channel to its floodplain (in incising or degrading conditions).

Channel gradient change is often the result of channel length adjustment, as occurs when an historic meander is re-activated. Channel bed elevation may be modified, typically by being raised and stabilized, in conjunction with restoration of an incised channel.

Measures to Increase Complexity

Rehabilitation of channel bed and profile generally focuses on the development, or retention, of pool-riffle sequences in low gradient streams, and step-pool sequences in high gradient streams (Chin 1989). Research has demonstrated that the pool-riffle unit is the primary hydraulic and morphologic control of bed scour, and of sediment transfer and deposition (Richards 1976, Keller 1971). Development and retention of pool-riffle and step-pool sequences are often accomplished by direct construction of pools, riffles and step-pools, or by installation of structures such as log sills to promote pool and bar establishment and retention (Gore and Shields 1995, Elliot and Mason 1985, Edwards et al. 1984, Lisle 1981). These techniques have been used extensively despite limited scientific evaluation of their long-term efficacy.

Riffles and Pools

Many efforts to establish pool-riffle sequences have relied on excavation of pools, and construction of riffles (Gore and Shields 1995, Elliot and Mason 1985, Edwards et al. 1984, Lisle 1981). The distances between pools are often based on empirical information available in the literature. A spacing of 5-7 channel widths between pools is widely accepted (Leopold et al. 1964, Thorne et al. 1996). However, pool spacing on the order of 2-4 channel widths has been reported on some streams (Rinaldi and Johnson 1997). In the presence of high woody debris loading, Montgomery et al. (1995) found pool spacing to decrease to as low as one channel width on pool-riffle systems.

Estimating pool depth has been approached from several angles. Hoffmans and Verheij (1997) presented a formula for the scoured depth of pools on channel bends. The formula was based on flume experiments and experiments in large rivers with mean particle diameters ranging from 0.3 to 63 mm. Maynord (1996) also presented an equation for predicting the scoured pool depth in bends. The Maynord (1996) analysis was based on data collected from the Mississippi River. Both of these equations were developed on large rivers and, especially in the case of Maynord's work, are based to some degree on sand-bed channels. As such, these equations are relevant only to smaller streams and gravel-bed streams with caution. Hoffmans and Verheij (1997) also suggested that the flow depth (upstream and downstream of a channel bend) may be used as a rough approximation of the pool scour depth in a bend. That is, stream depth in bends is roughly twice the depth found in straight sections. The range of applicability of this estimate was not indicated.

Construction of artificial riffles by placement of gravels within the cross-section can be a time-consuming and expensive task, and results of riffle construction projects have been varied. Artificial riffle construction on the Ohio River yielded no improvements in habitat because the designed riffles eroded or were covered with sand during high flows (Miller et al. 1983). Conversely, riffle construction on the Tombigbee River in Mississippi with course sand and gravel resisted high flows and resulted in approximately a two-fold increase in macro invertebrate and fish taxa after two years (Miller et al. 1983). Leopold et al. (1964) reported that efforts to develop pool-riffle morphology on dredged, gravel bed streams in Scotland resulted in natural-looking pools and riffles that persisted over a number of years. Despite such successes artificial riffle construction may provide only short-term habitat improvement as dynamic channel processes may lead to abandonment or disruption of constructed riffles.

Step Pool Units

Step pool morphology is associated with relatively steep channels that are typically constrained by valley walls. Rosgen (1996a) reports step pool units as existing on streams with gradients of approximately 0.04 to 0.10, while Grant et al. (1990) indicate that step pool morphology in study streams had an average slope of 0.17. Pool spacing in these streams varies from 1 to 4 channel widths (Chin 1989). Duckson and Duckson (1995) offer a comprehensive literature review of step-pool morphology, and describe step pool morphology in bedrock streams. Step pool characteristics in bedrock channels were dictated to some degree by lithology, though hydraulic characteristics were common to all lithologies. Grant et al. (1990) reported that natural structural units (such as step-pools) in high-gradient streams appeared to be formed by discharge events with return periods in the 50-yr range, and structure is controlled by particles representing the 90^{th} percentile or larger particle size. Based on these pool spacing and stability criteria, projects involving restoration or construction of small, headwater streams can apply techniques for woody debris and boulder placement to create step-pool units (Rosgen 1996a).

Structures that Promote Pool Formation

Structures and bends that are formed of resistant material can stabilize gravel channels and create aquatic habitat by promoting the formation of, and controlling the location of, pools and bars. One prerequisite for this channel control by bends or structures is that they occur in sufficient frequency (Lisle 1986). Large structures and armored bends may also stabilize channel courses by fixing the position of bars and pools. In addition, large structures may induce the formation of scour holes that could potentially precipitate localized bed degradation.

A number of alternative structures are used to create and maintain pool-riffle sequences. One technique frequently mentioned in the literature is strategic placement of large logs, or log weirs, across a river or stream (Gore and Shields 1995, Mesick 1995). These logs alter water flow on a small scale with the intention of recreating and maintaining pools and riffles. A significant drawback of log weirs is that they obstruct the waterways (Gore and Shields 1995), may alter channel profile by “drowning out” riffles (Frissell and Nawa 1992), and may cause channel widening. In addition, weirs, as with artificial riffles, may provide only short-term improvement of habitat. An extensive study of streams in the Pacific Northwest found a very high incidence of log weir failures with catastrophic releases of accumulated bed load and debris (Frissell and Nawa 1992).

Frissell and Nawa (1992) also discovered a high rate of failure or impaired effectiveness in single and clustered boulder structures. Nonetheless, the use of boulder structures to induce scour and thus create pools is common (Rosgen 1996a).

Measures to Provide Vertical Bed Stability

Vertical bed stability is generally a prerequisite for lateral stability. Degrading channels may cause catastrophic bank failure when critical thresholds of bank heights and angle are exceeded (Schumm 1977). If bed degradation is occurring, or is expected to occur, measures are often taken to reduce flow energy through flow modification or grade control structures. Aggrading channels tend to braid or migrate laterally as a result of middle or point bar growth. Bed aggradation can be arrested by controlling erosion in the watershed or upstream reaches, or by installing sediment traps or ponds (Federal Interagency Stream Restoration Working Group 1998).

Grade control structures are designed to enhance vertical bed stability by providing “hard points” that are resistant to channel downcutting. Grade control structures are applicable at natural or human-induced grade imbalances, such as knick points and head cuts, or at locations of culvert and bridge removals. Grade control structures are also used to maintain an elevation, for example, at an irrigation diversion intake, and in new channels to ensure grade stability. Grade control is typically achieved through the placement of large rocks at or near grade imbalances. Grouted boulders, for example, were a key ingredient in the rehabilitation of the South Platte River in Denver, CO (Federal Interagency Stream Restoration Working Group 1998). The design of rock grade control structures can be carried out with the guidance of one of the many existing riprap design manuals, such as USDOT (1989). Additionally, the U.S. Army Corps of Engineers (1999) presents detailed guidelines for grade control design using rock and/or concrete.

In small, headwater streams large woody debris can be used to create step-pool units to dissipate stream energy (Chin 1989). However, an extensive study of streams in the Pacific Northwest found a very high incidence of log weir failures, with catastrophic releases of accumulated bed load and debris (Frissell and Nawa 1992).

Ecological and Habitat Issues

The diverse hydraulic conditions generated by the pool-riffle unit provide a variety of biological niches. Tail outs provide spawning sites for salmonid fishes, pools offer refuge from high velocity flows and extreme temperatures, and riffles provide substrate for benthic invertebrates (Gore and Shields 1995). Attempts to create pool and riffle sequences through the construction of artificial riffles and pools may not yield these desired results if they are displaced or covered during high flow events (Miller et al. 1983). Habitat enhancement through modifications of the streambed profile requires consideration of the geomorphic and hydrological characteristics of both the reach and watershed, so that the constructed features will persist for a reasonably long period (Rosgen 1996a)

Additional Data Needs for Modification of Channel Profile

- Methods for estimating pool depth in small and medium-sized streams and coarse-bedded streams would facilitate accurate pool design.

Modifying Channel Pattern and Planform

Channel planform in alluvial channels is determined primarily by hydrologic character, expressed as a hydrograph, sediment load (Schumm 1977), and vegetation (Millar 2000). In non-alluvial channels, channel pattern and planform are determined primarily by geologic control. Channel pattern and planform may be altered to bring a disturbed, channelized or unstable stream into balance with its watershed characteristics.

Measures to Increase Complexity

Many fluvial systems have been straightened and/or channelized to improve flood conveyance and restrict bank migration. Channelization has lead to homogenization of the streambed and planform with subsequent loss of geomorphic function and habitat diversity (Schoff 1991). Specifically, channelization results in loss of pool-riffle sequences because many pools and riffles are associated with bends. Altering channel planform (particularly creating meanders) can increase channel complexity by stimulating the natural formation and maintenance of pools and riffles associated with meander bends.

Meander and Sinuosity

Meander restoration is a common technique used to bring a stream into balance with the hydrologic and morphologic characteristics of its watershed. The creation of meanders within a project reach can serve to dissipate excess stream energy, stabilize stream migration, decrease transport capacity and subsequent downstream sediment supply, and recover aquatic habitat (Johnson and Hey 1998).

Leopold and Langbein (1966) noted that a sine-generated curve approximates an idealized meandering river pattern. While many practitioners have applied this logic to channel design, Carson and Lapointe (1983) and Furgeson (1973) have concluded that the down-valley asymmetry of natural meanders cannot be adequately produced by applying symmetrical models.

Meander restoration designs can be based on empirical equations (Leopold and Wolman 1957, Williams 1986). However, the suitability of these equations is dependent on the similarity of the planform and hydraulic geometry of streams used to develop the regression equations and the streams in the region where the design will be implemented (Johnson and Hey 1998). Detailed stream reconnaissance can also be employed to verify the suitability of the empirical equations (Rinaldi and Johnson 1997).

Empirical equations are most often applied when one variable is known, such as a design discharge (Inter-Fluve 2000). Alternatively, reference reach based designs are preferred for undeveloped watersheds or watersheds that have been developed for many decades (Inter-Fluve 2000). Reference reaches can also be used to back up or double-check other design approaches. When no reference reaches are available or are inappropriate, empirical equations can be used. U.S. Army Corps of Engineers (1999) presents guidance for selecting from among the Leopold and Langbein (1966) sine-generated curve approach, empirical approach, and reference reach approach.

Influence of Vegetation on Channel Pattern

Bank vegetation can influence channel pattern by decreasing the erodibility of bank sediments (Millar 2000), thereby reducing the rate of channel migration. The extent to which vegetation exerts an influence on channel planform patterns appears to vary depending on the geologic, pedologic, physiographic, climatic, and hydrologic conditions of the watershed (Johnson and Hey 1998). Vegetation is most influential on smaller alluvial channels where it seems to be the dominant control of sinuosity (Ebisemiju 1994). Research by Millar (2000) on 137 meandering, braided and wandering rivers found that the density of bank vegetation exerts an important and quantifiable influence on channel pattern. This research demonstrated that vegetation removal could, along some streams and rivers, trigger transitions from meandering to braided patterns. This process should be reversible with the reestablishment of riparian vegetation in sufficient density to stabilize banks. Enhanced bank stability should lead to a narrowing of the channel and a subsequent return to the meandering pattern (Millar 2000). For a designed channel, establishment of vigorous bank vegetation should stabilize banks and allow a meandering morphology to persist.

Ecological and Habitat Issues

There are ecological consequences, both positive and negative, to adjustments in channel pattern and planform. Most negative effects are a result of poor design or implementation. Meander restorations, for example, may enhance the habitat value of the stream by re-establishing pool and riffle sequences, but only if they are appropriately designed to accommodate the flow and sediment supply in the watershed. Poorly designed alterations of planform geometry may result in significant channel adjustments with undesirable impacts on aquatic habitat (Johnson and Hey 1998, Rinaldi and Johnson 1997). Generally, if a stream is created with significant complexity, it follows that the biodiversity of the channel will also be correspondingly high, provided that there is appropriate biotic accessibility from upstream and downstream.

Modifying Channel Cross-Section

Channel design usually includes modification of the existing channel cross-section or the design of an entirely new cross-section. Determining appropriate cross-sectional dimensions is generally accomplished using one or more of the three common channel design approaches discussed earlier in this section: reference reach, empirical or analytical approaches. Modification of the channel cross-section is carried out for a number of reasons, including (but not limited to):

- Narrowing an over-wide cross-section to improve sediment transport in an area impacted by excessive deposition
- Widening or deepening to create a functional channel
- Raising of the bed of an incised channel to re-connect the channel and adjacent floodplain
- Lowering channel banks to re-connect the channel with a constructed, inset floodplain
- Creating an asymmetrical cross-section in a formerly plane-bed reach
- Placing structures to affect local hydraulic conditions (e.g., to induce the formation of scour holes or gravel bars) or to enhance aquatic habitat.

The science and status of understanding of channel cross-section modification is addressed in previous sections of this document, primarily those discussing approaches to channel design.

Reconstruction or Stabilization of Stream Banks

Most channel cross-section modification efforts require reconstruction of stream banks, and many bank stabilizations projects directly or indirectly modify channel cross-sections. Cramer et al. (2000) discusses the Washington Integrated Streambank Protection Guidelines (WISPG) document, which contains comprehensive guidelines for selection of streambank protection methods in Washington State, and is the recommended reference for streambank design. U.S. Army Corps of Engineers (1999) also provides guidelines for streambank design and construction. The Corps of Engineers (1999) document categorizes bank reconstruction as armor protection, indirect protection, or vegetation. Miller and Skidmore (1998) and Miller (1999) present the concept of deformable bank construction in contrast to more traditional non-deformable constructed stream banks. Deformable banks offer initial stability while vegetation becomes established, but once vegetation has become established, are susceptible to natural erosion processes to contribute to natural channel process.

Both the WISPG and the Corps of Engineers document provide criteria for selection of appropriate measures. The WISPG criteria direct practitioners toward specific techniques, while the Corps of Engineers offers general guidance. Since the level of detail concerning the status of the science of streambank protection is available in the related WISPG documents, further discussion is limited in this paper.

Stream corridor construction or restoration may require stabilization of stream banks for a period of years or decades. Even when project objectives include re-establishment of natural patterns of flow and channel migration (including channel adjustment through erosion and deposition), banks may need to be stabilized for a period of years while vegetation establishes to avoid accelerated erosion and the potential failure of re-vegetation efforts (Miller 1999). In the past, structural techniques such as surface armoring (blocks, rubble, concrete or rip rap) dominated bank stabilization efforts, and numerous references provide design guidance of these techniques (USDOT 1988 and 1989). These techniques may be appropriate if land use objectives do not allow for stream migration, but such "hard engineering" approaches generally result in loss of channel complexity and reduced fish densities (Peters et al. 1998).

Many of the streambank design approaches discussed in Washington Department of Fish and Wildlife (2000) utilize the principles of bioengineering to create a stable, yet naturally functioning streambanks. Bioengineering techniques incorporate live, native species and natural materials, sometimes in combination with hard structures, to provide erosion control and restore riparian function (Goldsmith and Larson 1997). Bioengineering approaches generally require less long-term maintenance, but installation is often limited by dormant seasons and skilled labor needs are high (Franti 1998). In addition, bioengineering designs must incorporate careful analysis of hydrologic and geomorphic conditions to ensure long-term bank stabilization and appropriate species selection (Goldsmith and Barrett 1998, Miller 2000). Bioengineering designs must consider the bankfull cross-sectional dimensions of the channel and the flooding tolerance and rooting depths of selected species. Ideally, planting zones should mimic the riparian community in stable reaches (Hoitsma 1996 and Miller 1996).

Disturbed or constructed channels generally lack cohesive material and root structure. A variety of techniques are used to stabilize soil while vegetation establishes. Techniques include: brush fascines, brush layers, brush sills, crib walls, willow posts, coir (coconut-husk fiber), fascines, (Goldsmith and Larson 1997) synthetic geogrids (Sotir 1998) and fabric encapsulated soil lifts (Fotherby et al. 1998; Miller 1996, 1997 and 2000). These and other bioengineering methods can offer immediate soil reinforcement to a depth of 12 feet (Sotir 1998).

Sotir (1998) reviewed 15-year case histories of four urban and rural watershed bioengineering projects in the southeast United States. All projects yielded well-vegetated, stable banks, enhanced habitat and aesthetic improvements. In one studied project, bioengineered banks remained stable despite a 100-year flood event 4 months after project completion. Bioengineered stream banks grow stronger with time as woody vegetation develops (Miller 2000). Stream banks along New Jersey's Raritan River constructed with fabric encapsulated soil in 1997, and planted with 40 different plant species, survived extreme floods associated with Hurricane Floyd in 1999. According to the National Weather Service (1999), this event produced the highest flood levels in 200 years, but bioengineered stream banks sustained almost no damage (Miller 2000). In contrast, some natural reaches of this river suffered severe erosion.

Measures to Enhance Habitat and Increase Complexity

Habitat enhancement efforts can take a variety of forms, from channel cross-section manipulation to in-stream fish habitat improvement structures and substrate alterations. Habitat enhancement efforts are most successful if they are approached from a basin-wide, process-oriented perspective. Neither in-stream structures nor channel modifications can compensate for degraded watershed conditions.

Increased complexity, in the form of roughness elements such as woody debris and boulders, effect affect local hydraulic forces which in turn produce a diversity of channel form and substrate conditions (Lisle 1981). Such diversity of channel form and substrate provides important habitat to fish and the organisms upon which fish prey. Common approaches toward increasing channel cross-section complexity are discussed below.

In-Stream Structures

In-stream structures have been widely used in stream restoration/enhancement projects. These structures typically include large woody debris, gabions (Gore 1985), and/or boulders installed individually or in clusters (Rosgen 1996a). However, there have been a great number of structure types and materials employed to provide habitat and increase diversity in streams. State of California (1998) offers an excellent overview of structure types, materials, and strategies. Although there is debate about the appropriateness of structures on certain types of streams, Rosgen (1986) offers explicit guidance on this matter.

Because the vast majority of instream structures intended to provide habitat and increase diversity are constructed of wood, stone, or a combination of the two, these types of structures are addressed in a general fashion below.

Structures have been favored over more basin-wide approaches to habitat enhancement primarily due to institutional and bureaucratic factors (Frissell and Nawa 1992) and the inherent financial and political difficulties in addressing the problem on a basin-wide scale. In an effort to foster a more broad-based approach to structure design, Shields (1983) suggests a general approach including:

- Planning location of structures to avoid degradation of existing habitat resources
- Selecting structures based on their ecological purpose
- Sizing structures to function within the normal range of flows from base to bank full
- Investigation of the hydraulic effects of structures
- Consideration of structure effects on sediment transport
- Selection of natural materials, preferably from near the site.

Important items that might be added to this list include:

- Understanding of channel dynamics (of sediment, water, and wood) and watershed use patterns

- Understanding the limited life expectancy of structures in dynamic systems

- Understanding conditions that may be limiting the biological productivity of the stream.

Woody Debris

Maintaining a Healthy Riparian Corridor—The most sustainable method of restoring LWD is to maintain an adequate riparian zone along the stream banks that will naturally contribute LWD to the stream (Swanson et al. 1976). Stream bank erosion, mudslides, and wind trigger LWD to fall into streams (Swanson et al. 1976). Management objectives that call for maintenance of healthy riparian forests will eliminate the need for expensive additions of LWD to streams.

Installing Woody Debris—Woody debris has been utilized for decades as a means of increasing complexity (e.g., scour holes and cover) in streams, and there are a great number of references describing methods for woody debris installation (Gore 1985, Rosgen 1996a, State of California 1998). Most often, tree trunks with root wads attached are considered to be the most desirable form of woody debris. When included, these root wads are typically oriented upstream into oncoming flow (State of California 1998). Woody debris is typically installed without anchoring or by fixing it in place with an anchoring system (Reich and Kershner 2000). Anchoring methods vary from simply burying a portion of the woody debris in bank or bed material to anchoring using stones, cables, bolts, or other such materials (State of California 1998).

Engineered log jams, which mimic natural log jams in which large woody debris is anchored only by its own weight, have also been installed and show promise in some situations (Abbe et al. 1997). Abbe and Montgomery (1996) described common locations for formation of natural log jams, and identified the apparent requirement for the deposition of a large, immobile "key member" log to initiate natural log jam formation. Abbe and others are currently developing guidelines for construction of engineered log jams as bank protection and habitat structures (NRCS 2001).

Generalized design methodology for woody debris installation has only recently become available. Castro and Sampson (2000) present a method for engineering-based analysis of woody debris stability. Braudrick and Orr (2000) use an empirically-based model to predict wood stability in streams. D'Aust and Millar (1999) provided guidelines for ballasting of woody debris structures. Robison and Beschta (1990) provide empirical relations, from coastal streams in southeast Alaska, for coarse woody debris dimensions and frequency of debris jams as a function of stream size and stream order, and also provide empirical data that may be used to design the orientation of coarse wood in stream channels. Bilby and Ward (1991) compared pool characteristics relative to large woody debris characteristics in old-growth and second-growth forests. Results from their study may assist designers in developing appropriate woody debris distributions for designed channels.

Additional Data Needs for Using LWD to Increase Habitat Complexity

- Additional empirical studies that provide regionalized characterization of appropriate density or frequency of woody debris placement.

- Woody debris installations are often seen as posing a risk to recreational boaters while in place and to downstream infrastructure if dislodged. Diedrich (2000) proposed more active examination of the conflicting objectives of recreational boating and habitat creation using woody debris.

Boulders and Spawning Gravel

Boulders and Boulder Structures—Boulders and gravel are used to increase the availability of spawning areas for fish and increase the diversity of habitat (Matthews 1990). Boulders, boulder clusters, and boulder flow deflectors are typically employed to induce the formation of scour holes and associated bars. Boulder weirs are often used to concentrate flow into plunge pools. Guidance on installation of boulders and boulder structures can be found in numerous publications including Gore (1985), Rosgen (1996a), and State of California (1998). In addition, Rosgen (1996a) and State of California (1998) rate the potential effectiveness of several boulder structures based on the morphology of the stream types.

Spawning Gravel—If spawning is limited by streambed conditions, but an adequate supply of gravel is present, spawning habitat may be enhanced by adding obstructions (such as boulder clusters or weirs) to a cross-section. Obstructions will lead to differential sorting of gravels and creation of depositional areas with appropriately sized gravel for spawning (Lisle 1981).

If sufficient gravel is not present within the stream, gravel additions may be warranted. Spawning gravels can be sized based on the species of fish and its size. Fish can generally spawn in gravels with median diameters up to about 10% of their body length; however, spawning gravels should be selected based not only on particle size used by fish but also on factors such as water depth and velocity (Kondolf and Wolman 1993). In regulated rivers, where dam releases are relatively sediment free, additional bed substrate can be added in order to allow for the buildup of gravel bars to be used for spawning (Kondolf 1996). Guidance on installation of spawning gravel can be found in numerous publications including Gore (1985) and State of California (1998). Gore (1985) covers the chemical, hydraulic, and physical parameters necessary for the successful development of the incubating eggs in the gravel, while the State of California (1998) publication covers the placement of imported spawning gravels.

Performance of Installed Structures

Roper et al. (1998) suggest that durability is probably greatest for in-stream structures used in constrained reaches of small to moderate sized streams (fourth order and smaller) and connected to the stream bank. However, the relationship between in-stream structure durability and upstream variables, including probability of high flow events and sediment transport variables, indicates the importance of a basin-wide perspective when implementing stream restoration projects (Hartman et al. 1996, Roper et al. 1998). Therefore, in-stream structures are most appropriate when used as short-term tools to improve degraded stream conditions while activities that caused habitat degradation are simultaneously modified (House and Norton 1996).

Although woody debris installation in streams has been a widespread practice for many years, relatively little scientific evaluation of its effectiveness has been conducted (Frissell and Nawa 1992). In their study, Frissell and Nawa (1992) examined 161 stone and wood structures in Oregon and Washington. The structures had been subjected to flows of the 2-yr to 10-yr return interval, depending on location. The structures were evaluated in terms of their stability and apparent hydraulic function. Failure or impairment of function was discovered at more than 50% of the log weirs, log deflectors, multiple-log structures, and boulder clusters examined. Cabled large woody debris and individually placed boulders fared worse, with failure or impairment of function rates of approximately 75% and 55%, respectively. Frissell and Nawa (1992) observed additional adverse effects resulting from construction of in-stream structures including: accelerated bank erosion, felling of streamside trees for construction materials, uprooting of riparian trees used to anchor structures, and catastrophic release of bed load and debris with structure failures. These results highlight the need to consider physical and biological phenomena at the watershed scale when designing restoration or channel construction projects.

Slaney et al. (2000) examined 13 stone-ballasted wood structures in a relatively large (40 m channel width) stream in British Columbia. Structural stability, hydraulic function and utilization by juvenile and adult rainbow trout were evaluated for several years after structure installation. The majority of the structures remained stable, although a few were displaced by bankfull floods. The rainbow trout population on the test reach was found to be 4 times that of a control reach, with 85% of the trout in the treated reach being associated with the wooden structures.

Heller et al. (2000) evaluated the structural stability (in terms of the presence or absence of displacement) of nearly 4,000 structures in Oregon and Washington. The structures were primarily constructed of logs, boulders, or combinations of the two. A high level of durability was discovered. Despite having weathered large flood events, fewer than 20% of the structures had been displaced.

Boelman et al. (1997) assessed the hydraulic performance of boulder clusters installed as habitat improvement structures in the St. Regis River in western Montana. During the assessment the river experienced a flood estimated to be in excess of a 25-yr return interval. Some cluster sites experienced formation of large scour holes and the associated small, downstream gravel bars. Other sites were deposition-dominated, with relatively small scour hole formation and significant amounts of sediment deposition around the clusters. The authors ventured no explanation for the different performance of the various cluster sites, pending further monitoring and analysis.

Design of the Channel Bed

Design of the channel bed is generally accomplished using one of the three common approaches to channel design, reference reach, empirical and analytical, as discussed previously in this chapter. Channel bed design includes consideration of bedform variability for habitat function, bed substrate sizing, bedload transport, and integration of habitat structure (Inter-Fluve 2000). Constructed or modified channel beds can be designed to be mobile, and thereby provide for dynamic process and natural substrate sorting, or immobile. Further detail on substrate sizing and bedload transport is summarized in the previous Sediment Transport Analysis section.

Ecological and Habitat Issues

Introduction of woody debris can improve fish habitat by increasing types and sizes of pools for fish refuge (Skaugset et al. 1996) adding cover (Richmond and Fausch 1995), and stabilizing critical spawning areas (House and Crispin 1990). It is likely that installed woody debris creates more, and more valuable, fish habitat than boulder installations. Research by Ramquist (1995) comparing sites with and without woody debris found the highest fish taxa richness in woody debris sites. These results suggest that woody debris has a positive effect on most fish species due to increases in cover and food supply. The best, sustainable method for stream habitat restoration may be provided by preservation and development of riparian forests (House et al. 1989), as this will insure a sustainable source of woody debris for streams.

Bank stabilization can have either positive or negative impacts on aquatic and riparian habitat. Application of hard engineering techniques can alter geomorphic function and lead to channel homogenization with subsequent loss of aquatic habitat. Riparian habitat is also impacted from these techniques. For example, seedling establishment in native riparian cottonwood forests depends on bare mineral soils resulting from disturbance associated with flood events and channel migration (Stettler et al. 1996). In contrast, non-native riparian species such as Russian olive do not require disturbed substrate to establish. Consequently, restricted channel migration due to bank stabilization may be contributing to a shift in the composition of western riparian areas from native cottonwood forests to forests dominated by Russian olive (Howe and Knopf 1991).

In contrast, bioengineering approaches can enhance riparian and aquatic habitat by providing vegetative cover for aquatic and terrestrial organisms. If compatible with project objectives, bioengineered banks can be designed to be deformable (Miller and Skidmore 1998), thereby restoring fluvial function, floodplain access, and rejuvenation of riparian forests. Sotir (1997) provides guidelines for selection of specific bioengineering vegetative methods that meet specific environmental objectives such as aquatic and riparian habitat improvement, and water quality protection.

Additional Data Needs for Habitat Enhancement

- Additional guidance on the optimal configuration, density, and installation techniques for habitat improvement structures such as woody debris and boulders would facilitate their effective installation.

- The continuing development of new materials and techniques used to construct bioengineered banks will provide additional alternatives to future designers.

- Additional monitoring of the function and stability of installed structures and streambanks is needed.

Creating and Adjusting Secondary and High Flow Channels

Secondary channels are channels that do not contain the main flow of the river. These channels may be spring fed, may contain main channel flow only during high water events, may serve as backwater areas, or any combination of these possibilities. In the Pacific Northwest, secondary channels have been constructed to mitigate loss of spawning and rearing habitat (Bonnel 1999, Washington Department of Fish and Wildlife 2000). These channels also allow for river interaction with the flood plain, thereby keeping riparian vegetation healthy and providing cover for fish.

Ecosystems of large, undeveloped rivers are based on interactions between the main channel and adjacent low-velocity habitats during weeks of over bank flooding (Welcomme 1989). Spatial and temporal habitat heterogeneity is created by erosion and deposition as the channel migrates back and forth across the floodplain. It follows that restoration of large rivers to a pristine or virgin state is often incompatible with present human population levels (Welcomme 1989). Instead, the logical goal is the rehabilitation of developed river systems, that is, the recovery of some of their ecological function and value (Gore and Shields 1995).

Flow Regimes

There are several design issues relating to placement and long-term function of secondary channels. One of the first considerations is discharge. Hill et al. (1991) propose four different streamflow regimes: instream flows, channel maintenance flows, riparian maintenance flows, and valley maintenance flows. Knowledge of fluvial-geomorphic processes that create and maintain streams and how aquatic and terrestrial ecosystems function synergistically is fundamental to identifying flows that maintain fish habitats and, ultimately, fish biomass and diversity. Protecting these elements with multiple flow recommendations is necessary because of these ecological linkages (Hill et al. 1991). Both the discharge at which the channel will become active and the discharge capacity of the channel need to be considered. With the discharge established, the bed material can be sized according to the shear stresses and the amount of projected scour. Also to be considered while sizing the bed material is what life stage and what type of fish will be using the channel or are desired in the channel.

Percolation-Fed Channels

Fish habitat in overflow channels is frequently unstable and prone to flood damage and channel shifting. Channels supplied primarily by groundwater are generally more stable because they are protected from flooding. These percolation-fed channels may provide ideal sites for spawning and refuge for juvenile fish (King and Young 1982). According to Bonnell (1991), construction of percolation-fed channels requires:

- Identifying an area where the channel could outlet and attract fish
- Surveying water elevations upstream, adjacent and downstream of the proposed channel
- Evaluating groundwater flow potential
- Monitoring river flows and ground water levels for at least one full year.

Ecological and Habitat Issues

The role of vegetation in the river corridor and the value of floodplain ponds as refuge and nutrient sources are important considerations in restoring ecosystem integrity (Gore and Shields 1995). Backwater habitat values are dependent upon at least seasonal if not continuous hydraulic connection to the main river channel (Gore and Shields 1995). Ecological values of floodplain habitats along levied rivers can sometimes be restored by constructing new levees more distant from the channel (so-called setback levees). Setback levees permit controlled inundation of adjacent floodplains and allow the river to meander within a belt-width prescribed by levee dimensions (Gore and Shields 1995).

Additional Data Needs for Creation of Secondary Channels

- Channel designers would benefit from additional guidance on the optimal configuration and construction techniques for side channel construction/enhancement.

Incorporating Vegetation in Stream Channel Design

Vegetation plays a vital role in the natural function, geomorphology, and biologic health of streams. The combined effect of roots and stems provide varied but considerable erosional resistance to otherwise vulnerable streambanks and floodplains. Below the soil surface, dense roots of both herbaceous and woody vegetation physically bind soil particles to resist detachment and erosion (Gray and Sotir 1996). Above ground, uniform coverage of stems and shoots can absorb and dissipate erosional forces on the soil surface (Copeland 2000), and in sediment-laden water, encourage sediment deposition (Coppin and Richards 1990). Millar and Quick (1993) and Zimmerman et al. (1967) emphasize the role of bank vegetation characteristics in providing for bank stability which controls channel geometry.

One of the most important design factors in successful revegetation of reconstructed streambanks is selecting species with the appropriate inundation tolerance. A common approach to sorting potential plant species by tolerance to inundation and subsequent falling water tables is the of Reed's (1998) regional indicator status (e.g. Facultative Wetland, etc.) of the "frequency of occurrence in wetland or non-wetlands". While this technique was not the intent of the publication (Thurnhorst 1993), it is one of the few comprehensive sources to qualitatively describe the relative distribution of native riparian and wetland plants across a range of inundation regimes. Because of the inherent tolerance to regional moisture and drought characteristics, bioengineered bank treatments typically incorporate site-adapted native riparian plant materials.

An additional consideration is vegetation tolerance to shear and the ability to withstand erosive forces. Ideally, channel design considers the species and age class of vegetation in designing banks, in order to address anticipated shears. However, published values for vegetal resistance to shear are limited. Hoitsma and Payson (1998) provide a comprehensive literature review of vegetal resistance to shear stress.

Washington Integrated Streambank Protection Guidelines contains comprehensive guidelines for streambank construction in Washington State, including detailed discussion on incorporation of vegetation in channel and bank design.

Additional Data Needs for Vegetation in Channel Design

- One the largest literature gaps in incorporating vegetation in natural channels is the quantification of the shear stress resistance of woody plants, especially frequently used native species such as willows and dogwoods. While there is a similar lack of data on shear stress resistance of native herbaceous plants, sources such Chen and Cotton (1988) and others are available on several non-native species, which have somewhat analogous growth forms and rooting habits.

- The bulk of vegetal shear stress literature is undertaken on flumes and grass-lined waterways, which are far more uniform in slope and cross-section than most natural channels restoration practitioners must work with.

- Most data is based on short duration studies (Hoitsma and Payson 1998).

Channel Design in the Urban Environment

The urban environment poses unique channel design challenges. Urban channel design and restoration efforts are typically restricted by site conditions and limitations, and must address severely altered hydrologic character and sediment supply. Site limitations often include limited easement width, road crossings, and underground utilities (Alexander et al. 1994). Under such conditions of altered hydrology and sediment supply, and with considerable site constraints, the complete restoration of natural channel geometry and biologic function is rarely possible (Goldsmith and Barrett 1998).

Altered Hydrologic Regime

One of the most important factors defining an urban channel is an altered hydrologic regime. As a watershed is developed, impervious surfaces such as roofs and pavement quickly shed runoff, resulting in overland flow of runoff that was formerly conveyed primarily by subsurface flow (Booth and Jackson 1997). The transport of runoff to streams by gutters, drains, and storm sewers adds to the "efficiency" of developed areas' ability to quickly shed runoff (Booth and Jackson 1997). The development of a significant level of impervious surfaces and drainage networks within a watershed has been shown to have the following effects on basin hydrology:

- Increase in peak flow magnitude
- Increase in watershed response time, or "flashiness"
- Lower summer base flows (Henshaw and Booth 2000, Finkenbine et al. 2000).

Finkenbine et al. (2000) stated plainly that "increased imperviousness results in larger and more frequent floods, greater total surface runoff, and decreased time to produce runoff."

Quantifying the level of development within a watershed that is likely to result in channel degradation has been examined by a number of authors (Booth and Jackson 1997, Henshaw and Booth 2000, Schueler 1995). The methods for quantifying urbanization, and the levels of urbanization likely to adversely impact channel stability and aquatic habitat, continue to be explored and need refinement before they can be applied as predictive tools. In western Washington, Booth and Jackson (1997) found channel instability and decreased quality of fish habitat on watersheds with about ten percent (or more) effective impervious area (EIA). Examining streams in seven developed and developing watersheds in western Washington, Henshaw and Booth (2000) concluded, "the overall physical form of many Puget Sound lowland streams can withstand high levels of urbanization pressure." Using a more liberal definition than EIA to quantify "watershed urbanization," Henshaw and Booth (2000) observed minor channel instability in watersheds that were as little as 50 percent urbanized. Significant instability was observed only in watersheds that were greater than 90 percent developed.

The implications of altered hydrology on channel stability and the approach and practice of channel design cannot be understated. Significantly changed hydrology is probably the principle driver of urban channel degradation (Finkenbine et al. 2000).

Common Changes in Urban Channel Form and Function

Channel Expansion

Channel expansion has been noted to occur in response to watershed urbanization in a variety of climatic and physiographic regions (Finkenbine et al. 2000, Henshaw and Booth 2000). This expansion has been attributed to a number of factors, most importantly the increase in peak flows that typically follow urbanization (Henshaw and Booth 2000). Increased peak flow yields a corresponding increase in sediment transport capacity of a channel, which leads to accelerated erosion of the channel bed and banks. Infrequently, channel expansion may occur by the buildup of overbank deposits, which increase bank height (Henshaw and Booth 2000). Other factors that contribute to channel expansion include straightening, deepening, and lining of channels (e.g., with concrete), removal of riparian vegetation to increase flood conveyance, and lateral constraint of channels by armoring channel banks (Booth and Jackson 1997).

Impaired Riparian Function

Riparian vegetation on the floodplain and streambanks provides a buffer to help mitigate the impacts of urbanization (Finkenbine et al. 2000). Such vegetation provides significant strength to streambanks, provides temperature-regulating shade to the stream surface, and acts as a source of large woody debris. Riparian vegetation is primarily removed by bank erosion and by municipalities as a means to increase flood conveyance. On many urbanized streams, accelerated bank erosion and restricted channel corridor width leave little room for riparian vegetation.

Changes in Sediment Dynamics

As a stream is destabilized by urbanization, sediment dynamics pass through two stages (Finkenbine et al. 2000). Initially, increased sediment inputs from construction activities and increased bank erosion (caused by heightened peak flows) result in an increased sediment load. Once watershed urbanization is complete and the hydrologic regime has stabilized, bed coarsening is observed as sediment inputs stabilize at relatively low levels, but channel competence remains relatively high (Finkenbine et al. 2000).

Finkenbine et al. (2000) also found streambed gravels to have less fine material and higher intra-gravel dissolved oxygen concentrations than gravels in comparable rural streams. They attributed this high gravel quality to increased peak flows and, subsequent to stream re-stabilization, relatively low sediment inputs. However, anadromous salmonids “depend on a particular combination of water and sediment fluxes to maintain favorable channel conditions” (Booth and Jackson 1997). It is conceivable that the coarsening of bed sediments and reduction of sediment supply believed by some authors to be characteristic of the later stages of channel re-stabilization can signify a significant reduction in habitat quality from historic conditions. For instance, if the gravel that remains after bed coarsening is too large to be suitable for spawning, and the input of optimal spawning-sized gravel is limited, a stream may provide very little spawning habitat. Prior to urbanization, such a stream may have ordinarily transported, sorted, and deposited, bedload containing a large fraction of gravel suitable for spawning.

Loss of Woody Debris

As a watershed becomes urbanized, woody debris is more readily flushed out by the increased peak flows (Finkenbine et al. 2000). In addition, as stated above, the recruitment rate of woody debris is often diminished significantly by degradation of riparian vegetation. Edmonds et al. 2000) found 2 pieces of large wood in an urbanized segment of stream in Victoria B.C., while a comparable length of non-urbanized stream held 56 pieces.

Urban Channel Response and Recovery

While some authors have asserted that channels disturbed by urbanization will remain unstable indefinitely, there are a number who believe that, through natural geomorphic response, urban channels can stabilize after urbanization (Finkenbine et al. 2000, Henshaw and Booth 2000). Upon studying seven urbanized channels in the Seattle area, Henshaw and Booth (2000) concluded that channels can remain stable or and/or re-stabilize under relatively high rates of watershed urbanization. They add, however, that channels in extremely urbanized basins are progressively more likely to stabilize very slowly or not at all. Also at highest risk, according to Henshaw and Booth, are streams bedded in intrinsically erodible sediment.

Finkenbine et al. (2000) state, “Past studies indicate that, if a stream is not constrained, it will adjust to urbanization.” Such adjustments will include cross-section dimensions and a sediment transport regime that are in equilibrium with the flow regime (Finkenbine et al. 2000). The time required for such adjustments is unknown. Finkenbine et al. (2000) studied streams in British Columbia that drained watersheds urbanized approximately 20 years earlier, and considered them to be re-stabilized. Henshaw and Booth (2000) concluded that “channel re-stabilization generally does occur within one or two decades of constant watershed use, but it is not universal.” The findings of these authors indicate that in some (or many) cases, channels are capable of natural re-stabilization after urbanization.

Typical Approaches to Urban Stream Channel Design

Technically, urban stream channel design approaches do not differ significantly from those approaches listed previously in this chapter. The main difference may be that urban channel designs will tend to involve “harder” methods of bank and bed construction. Traditionally, channel design in urban settings has been oriented toward flood control, wastewater management, and other forms of protection. This heavier-handed approach to channel design is often necessary to address the relatively high hydraulic forces, space constraints, and infrastructure and property protection restrictions inherent in the urban environment (Inter-Fluve 2000). Approaches to urban channel design to provide natural function are largely undocumented. Most project and approach documentation exists as limited design reports. Project monitoring reports or documentation is largely absent from the literature.

Approaches to channel design in urban settings are fundamentally restricted by site-specific constraints and limitations, and by the greatly altered hydrologic, sediment transport, and vegetative character of the watershed. Site constraints and limitations include property boundaries, utilities, road crossings, and frequent grade controls in the form of culverts, bridges, weirs, and utility crossings (Inter-Fluve 2000).

Henshaw and Booth (2000) suggest that management response should not leap to impose channel stabilization measures, especially if the watershed is urbanized at a relatively low level or is still in the process of urbanization. In these cases, they suggest that stabilization is likely to occur naturally, and that heavy-handed intervention in the middle of the natural re-stabilization process is likely to do more harm than good. Protection of local habitat and mitigation of increased flows and downstream sediment load are, they suggest, a better use of resources. Finkenbine et al. (2000), after studying a number of streams that they considered to be re-stabilized, recommended the establishment of a healthy riparian zone and the in-channel placement of woody debris as the most beneficial stream restoration strategies for those streams.

Design Approach for Urban Channel Design

The Reference Reach and Empirical Design Approaches

Reference reach methodology is most appropriately applied to relatively pristine channels, in streams where the flow regime has usually not been significantly changed, or in otherwise stable channel systems. Such an approach to channel design may be applicable to urban channel design, but only if re-stabilized urban channel segments can be identified and used as reference reaches (Inter-Fluve 2000). Too often, however, designers may be attracted to using an inappropriate reference reach, or "target" channel type that cannot be sustained under the constraints of the urban flow regime, sediment supply, and the horizontal and vertical constraints imposed by private property and infrastructure.

The empirical design approach is similarly subject to limited applicability. Most empirical design guidelines were developed based on observation of relatively stable, natural channels (Leopold and Maddock 1953), making the use of such information in urban channel design questionable. The application of the reference reach and empirical design approaches in urban channel design may become more appropriate as they become better developed for urban settings. Specifically, methods for their application in strictly urbanized watersheds needs to be clarified and tested. Channel stability assessment methods such as that presented by Doyle et al. (2000) and U.S. Army Corps of Engineers (1999) will aid this effort by enabling development of empirical relationships and approaches within urbanized watersheds.

Alexander et al. (1994) used a combination of the reference reach and empirical approaches to determine channel cross-section dimensions and planform for an urban channel restoration project on a tributary to Lake Ontario. As a subsequent component of their design, a HEC-2 hydraulic model was used to confirm that the flood conveyance goals of the project would be met and that the proposed bank treatments were adequate to withstand the expected hydraulic forces. Ashfield et al. (1994) documented a similar design approach using Rosgen (1996a) channel classification to develop rough cross-sectional geometry and subsequent HEC-2 analysis to confirm the adequacy of the cross-section with respect to flood conveyance, and the structural adequacy of the proposed bank treatments.

Analytical Approach

The analytical approach allows sediment transport and channel conditions to be explicitly quantified through analysis rather than assumed, as in reference reach and empirical approaches. Thus, if the flow regime of an urbanized watershed has stabilized and sediment inputs can be quantified or accurately estimated, then a stable channel configuration can be determined analytically (Inter-Fluve 2000). This should also be true for watersheds that are in the process of developing, but for which the future (stabilized) flow and sediment input regimes can be estimated.

Furthermore, urban channel design often requires some degree of analytical approach. Many local laws require an assessment of the effects of proposed work on flood elevations (Morris 1996). The HEC-2, and more recently HEC-RAS, hydraulic models developed by the U.S. Corps of Engineers are the standard method for analysis and documentation of these effects. As projects in urbanized watersheds typically require the creation and use of such models for determination of floodwater surface elevation levels, they are generally available for use in testing and verification of proposed channel conveyance and stability (Alexander et al. 1994, Ashfield et al. 1994). As these models are easily modified to examine a range of restoration options, they also represent excellent tools for conducting all levels of design analysis (Morris 1996). Model output allows assessment of flood elevations, development of shear-based streambank and bed designs, estimation of channel scour depths at structures and streambank toes, and analysis of channel competence and sediment transport capacity.

Hydrologic Analyses

Hydrologic analyses within urbanized watersheds represent one of the greatest challenges in urban channel design, as detailed previously. Methods commonly employed to characterize hydrology within urban settings include segmented hydrographs and the application of stormwater runoff models (Inter-Fluve 2000). Because hydrologic character changes with urbanization, historic gage data is not appropriate. Gage records, therefore, must be segmented to isolate the relevant, or contemporary, character. This typically limits the relevant period of record may be limited to only a few years (Inter-Fluve 2000).

Urban hydrology is commonly derived using runoff models such as HEC-1 Flood Hydrograph Package developed by the Army Corps of Engineers or the U.S. Soil Conservation Service TR-20 model. Other models, initially developed for evaluating water quality in urban environments, include the Storm Water Management Model (SWMM), the Hydrologic Simulation Program Fortran (HSPF) (Maidment 1993).

Additional Data Needs for Urban Channel Design

- Methods for determining effective discharge in urbanized watersheds will greatly aid the development of urban channel rehabilitation and design.
- Additional guidance on assessing changes in, and stability associated with, flow regimes and channel morphology in urbanized watersheds.
- Development of empirical relationships and methods for urbanized channel systems.
- Methods for creating sustainable, high-quality aquatic habitat in watersheds with altered flow and sediment regimes need to be developed and tested.

Monitoring and Assessment of Constructed/Enhanced Channels

Monitoring Guidelines

The monitoring of project performance is an important component of channel design efforts. The U.S. Army Corps of Engineers (1999) summed up monitoring of stream rehabilitation measures as “essential for establishing requirements for maintenance and repair of features, for establishing performance of measures, and for providing an essential feedback loop to planning and design of future projects.” As a component of streambank protection projects, Washington Department of Fish and Wildlife (2000) defines monitoring as “the collection and assessment of repeated observations or measurements over time to evaluate the performance, and potentially the impacts, of bank protection treatments.” This same definition applies just as readily to stream channel design projects.

There are a number of guidelines available for monitoring many related components of channel design projects such as plant ecology, fisheries biology, geomorphology, and hydrology. Relevant guidelines and corresponding authors include the following:

- Common methods of aquatic habitat assessment (Bain and Stephenson 1999)
- Measuring and monitoring plant populations (Elzynga et al. 1998)
- Use of stream channel reference sites as monitoring tools (Harrelson et al. 1994)
- Inventorying and monitoring riparian areas (Myers 1989)

- Methods for evaluating riparian habitats with applications to management (Platts et al. 1987)

- A synthesis and directory of forty protocols for monitoring salmon habitat in Washington state (a Washington Department of Fish and Wildlife work in progress)

- Evaluating stream restoration projects (Kondolf and Micheli 1995)

- An integrated method of assessing project success based on physical, chemical, and biological factors (Gore 1985)

- General guidelines for the development of monitoring plans related to streambank protection (Washington Department of Fish and Wildlife 2000).

In particular, Cramer et al. (2000) provides guidelines to help develop a consistent monitoring protocol for streambank protection projects in the State of Washington. These guidelines are directly applicable to use on channel design projects.

Additional Data Needs for Monitoring

Cramer et al. (2000) identified a notable lack of published information on monitoring of composite streambank protection projects.

Recommended Outline for Channel Design Guidance Document

The following is a proposed outline for development of Channel Design Guidelines and is based on the Washington Integrated Streambank Protection Guidelines (WISPG) currently being developed by Washington Department of Fish and Wildlife (2000), Inter-Fluve, Inc.'s Process-Based Channel Design Short Course Manual (Inter-Fluve 2000), the multi-agency Stream Corridor Restoration, Principles, Processes and Practices document (Federal Interagency Stream Restoration Working Group 1998) and U.S. Army Corps of Engineers channel design guidelines (U.S. Army Corps of Engineers 1999). In order to provide standardization of guidelines within the State of Washington, it is recommended that the channel design guidelines be modeled after the format applied to the Washington Integrated Streambank Protection Guidelines.

Introduction

1. Definition of Channel Modification and Channel Design
2. Justification for Channel Modification Projects
3. Guiding Principles for Channel Design

Project Initiation and Planning

Problem Identification

1. Define Problem, evaluate in Site, Reach, and/or Watershed context
2. Define Objectives
3. Identify Stakeholders and Incorporate Interests in Objective
4. Identify Site Constraints, Limitations and Roadblocks, Permitting Requirements
5. Identify Potentials for Risk (to project, public, natural resource, etc.)

Characterize Project Reach

1. Characterize hydrology
2. Describe fluvial geomorphic conditions
   - Use descriptive, analytical and/or classification methods
3. Characterize sediment regime
4. Estimate hydraulic parameters
5. Identify vegetative community characteristics

Feasibility Assessment

1. Identify Alternatives
2. Develop Conceptual Design Solutions
3. Estimate Timeframes and Budgets
4. Select Alternative

Design Criteria

1. Design criteria relative to objectives, risk, and cost
2. Design Criteria as iterative, evolving standards through design process and stakeholder input
3. Develop Design Criteria based on stakeholder objectives, permitting limitations, and site limitations for each design component, including:

- ☐ Vertical Stability
- ☐ Lateral Stability and Streambanks, including Vegetation
- ☐ Fish/Aquatic Habitat
- ☐ Construction Criteria

<u>*Project Team Development*</u>

1. Identify Disciplines Needed
2. Assemble Project Team

Data Collection and Assessment

<u>*Data Collection*</u>

1. Hydrologic Assessment
2. Sediment Transport Assessment
3. Geomorphologic Assessment (including assessment of channel stability)
4. Assessments of Aquatic and Riparian Habitat and Function
5. Identification of factors limiting geomorphic and biologic function of stream

<u>*Problem Assessment*</u>

1. Site, Reach, and Watershed Context of Problem
2. Risk Assessment

Design Approach and Methods

1. Channel Design as an Iterative Process
2. Standardization of Channel Design Methodologies

<u>*Analog, Empirical, and Analytical Design*</u>

1. Analog and Reference Reach Design: Definition, Limitations, and Applications
2. Empirical Design: Definition, Limitations, and Applications
3. Analytical Design: Definition, Limitations, and Applications

<u>*Channel Cross-Section Design*</u>

1. Cross-section design to accommodate design discharge
2. Methods to determine cross-section characteristics
3. Floodplain design

<u>*Channel Slope Design*</u>

1. Channel Slope Considerations and Guidelines
2. Methods to Determine Channel Slope
3. Grade Control – Evaluation and Design

<u>*Sediment Transport*</u>

1. Methods to design and achieve sediment transport continuity
   - ☐ Address Sediment Transport Continuity through cross-section/slope iterations
   - ☐ Planform as a byproduct of sediment transport continuity
2. Channel Substrate Sizing

<u>*Channel Bank Design*</u>

1. Refer to or borrow heavily from WISPG
2. Deformable vs. Non-Deformable Banks

Aquatic Habitat Design

1. Fish Habitat – general discussion of habitat needs including nature of habitat and complexity, addressing all life stages
2. LWD Installation (refer to WISPG)
3. Spawning Habitat Design

Permitting

Identify Permitting Requirements

1. Identify Federal, State and local permits
2. Discuss project scope with permitting authorities

Prepare Permits

1. Prepare permit applications
2. Conduct site meetings as needed

Implementation

Project Construction

1. Construction Considerations:
   - ☐ Site Access
   - ☐ Seasonality – Hydrology, Fisheries and Revegetation
   - ☐ Erosion and Sediment Control
   - ☐ Subsurface Conditions
2. Sequencing
3. Dewatering: Methods
4. Fish Habitat Construction

Cost Estimation

Construction Oversight

1. Designer involvement
2. Design/build framework versus design-bid-build
3. Use of construction documents (plans and specifications)
4. Contractor experience

Monitoring

1. Development of a Monitoring Plan
2. Conducting Monitoring Activities

Contracting

1. Considerations for Contracting Implementation

Technical Appendices

Hydrology

1. Derivation of hydrologic statistics – urban and non-urban, gaged and un-gaged basins
2. Selection of Design Discharges
3. Dominant, Effective and Bankfull Discharge

Fluvial Geomorphology

1. Dependent and Independent Variables Determining Channel Form and Function
2. Dynamic Equilibrium defined
3. Defining a Natural Channel – List and Discussion of Channel Characteristics
4. Categorization of Natural Channels – Alluvial, Colluvial, etc.
5. The Role of Woody Debris in Channel Morphology

Sediment Transport

1. Sediment Characterization – Gradation and Volume
2. Sediment Transport Continuity
3. Methods of Measuring and Evaluating Sediment Transport

Hydraulics

1. Channel capacity
2. Flow Characteristics and Shear
3. Methods for Modeling and Evaluating Channel Hydraulics

Riparian Vegetation

1. Role of Plants in Channel and Bank Stability
2. Selection of Plant Species for Revegetation
3. Plant Forms for Revegetation
4. Monitoring Revegetation Efforts

Aquatic Habitat

1. Salmonid Habitat and Life History
2. Assessing and Inventorying Habitat

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APPENDIX A

Glossary of Terms

Glossary of Terms

Active revegetation: A strategy involving planting of seed, cuttings, containerized plants, salvaged plants or other plant materials to achieve a desired plant community.

Adventitious roots: Those that occur on plant stems in positions where roots normally are not found and are stimulated by dark, moist conditions associated with inundation and soil burial.

Aggradation: The process of building up a surface by deposition. An aggrading stream is actively building up its channel or floodplain by being supplied with more sediment load than it is capable of transporting. It is the opposite of degradation.

Alluvial stream: A stream that deposited the bed and bank materials of the channel perimeter under the present hydrologic regime. Alluvial streams have erodible boundaries and are free to adjust dimensions, shape, pattern, and gradient in response to change in slope, sediment supply or discharge.

Alluvium: A general term for sedimentary deposits created by streams on river beds, floodplains and alluvial fans. The term applies to stream deposits of recent time.

Anaerobic: Condition in which molecular oxygen is absent from the environment. This commonly occurs in wetlands where soil is saturated by water.

Anastomosed: Describes the river planform wherein there are multiple channels that are separated by vegetated, semi-permanent islands.

Anthropogenic: Man-made or man-induced.

Armor: The surficial layer of coarse grained sediments that are rarely transported and which protect the underlying sediments from erosion and transport.

Armoring: (a) The formation of an erosion-resistant layer of relatively large particles on the surface of the stream bed which resists degradation by water currents, resulting from removal of finer particles by erosion. (b) The application of various materials to protect stream banks from erosion.

Available water capacity: Ability of a soil to hold water in a form available to plants.

Bankfull discharge: The discharge corresponding to the stage at which the flood plain of a particular stream reach begins to be flooded. The point at which overbank flow begins.

Bar: (a) A ridge-like accumulation of sand, gravel, or other alluvial material formed in the channel, along the banks, or at the mouth of a stream where a decrease in velocity induces deposition. (b) An alluvial deposit or bank of sand, gravel, or other material, at the mouth of the stream or at any point in the stream itself which obstructs flow and induces depositions.

Base Level: The lowest level to which a land surface can be reduced by the action of running water.

Bed Load: The part of a stream's load that is moved on or immediately above the stream bed, such as the larger or heavier particles rolled along the bottom; the part of the load that is not continuously in suspension or solution.

Bed-load discharge: The quantity of bed load passing a given point in a unit of time, expressed as dry weight.

Bed Material Load: The part of the stream's total load that comprises the material in a streambed when it is dry. This material is usually composed of both bed load and suspended load material.

Bed roughness: A measure of the irregularity of stream bed materials as they contribute to resistance to flow. Commonly measured in terms of Manning's roughness coefficient.

Bend Ratio: A measure of the degree of curvature as represented by ratio of R_c/W, radius of curvature over width of river. Commonly used in bend scour equations.

Block/slab Failure: Failure by gravity of a coherent mass of material by vertical fall or topple where the underlying support has been removed (in this case, where a bank has been undercut by a stream channel).

Blown Out: Slang for deterioration or failure of a bioengineered stream bank, bed, or structure as a result of a high flow event. Appropriate action may include cursing the rain deities, drinking copious amounts of alcoholic beverages, and/or reviewing the classifieds for job openings preferably in real estate.

Braided: A stream that divides into an interlacing or tangled network of several branching and reuniting channels separated from each other by branch islands or channel bars.

Canopy coverage: The percentage of ground covered by the outline of an individual plant's foliage, or collectively covered by all individuals of a species within a stand or sample plot.

Cascade: Series of small vertical drops in a channel that may be natural, or be constructed from boulders and other natural materials.

Channel: A natural or artificial waterway of perceptible extent that periodically or continuously contains moving water. It has a definite bed and banks which serve to confine the water.

Channel Bed Slope, S_o: Syn. channel gradient. The ratio of vertical drop to horizontal distance of the channel.

Channel Energy Slope, S_e: The change in energy along the horizontal distance of the channel. In a non-pressurized, open channel system the energy is equal to the flow depth plus the velocity head.

Channel lag: Refers to the coarsest sediments in the river that are generally located in the thalweg region.

Channel pattern: The configuration of a stream. Described in terms of its relative curvature, it includes:

- straight: Very little curvature within the reach.
- sinuous: Slight curvature within a belt of less than approximately two channel widths.
- irregular: No repeatable pattern.
- irregular meander: A repeated pattern vaguely present in the channel plan. The angle between the channel and the general valley trend is less than 90 degrees.
- regular meander: Characterized by a clearly repeated pattern.
- tortuous meander: A more or less repeated pattern characterized by angles greater than 90 degrees.

Channelization: Straightening of a stream or the dredging of a new channel to which the stream is diverted.

Chute: A narrow channel through which water flows rapidly.

Clastic: Pertaining to a rock or sediment composed principally of fragments derived from pre-existing rocks or minerals and transported some distance from their places of origin.

Climatic year: A continuous 12-month period during which a complete annual cycle occurs. The USGS uses the period October 1 to September 30 in the publication of its records of streamflow. Also called water year.

Colluvium: A general term for loose deposits of soil and rock moved by gravity; e.g. talus.

Community (plant community): An assembly of plants living together reflecting no ecological status.

Competence: The maximum size of particle that a stream can carry. This is governed by water velocity.

Compound Channel: Nested channels in a flood plain with successive bank configurations corresponding to capacity for increasing flow events.

Concave Bank: The bank on the outside of a bendway.

Conveyance (K): The shape and roughness of a channel section.

$$Q = K\ S^{1/2} \text{ therefore } K = 1.49\ A\ R_h^{2/3} / n$$

Criteria: See design criteria.

Cross-Section: A transect in the vertical plane oriented across a channel or some other feature.

D_{50}: The median grain size diameter. An expression of the average particle size of a sediment or rock, obtained graphically by locating the diameter associated with the midpoint of the particle-size distribution; the middle most diameter that is larger than 50 percent of the diameters in the distribution and smaller than the other 50 percent.

Deformable: In reference to channel banks or boundaries, implies that the channel is free to change over time to maintain equilibrium or in response to changes input variables. Deformable banks are allowed to erode over time at rates which are controlled by natural process and checked by bank vegetation.

Degradation: The geologic process by which stream beds and flood plains are lowered in elevation by the removal of material. It is the opposite of aggradation.

Deposition: The settlement or accumulation of material out of the water column and onto the stream bed. Occurs when the energy of flowing water is unable to support the load of suspended sediment.

Design criteria: Project goals or specifications upon which a design can be based. Specific guidelines which designs must adhere to, values be designed to, and elements to include.

Detritus: Loose rock and mineral material produced by mechanical disintegration or abrasion, and removed from its place of origin.

Dewatering: Removing water from a defined area utilizing gravity or mechanical means.

Discharge: Volume of water flowing in a given stream at a given place and within a given period of time, usually expressed as m^3/sec.

Dominant Discharge: The discharge that has the greatest impact on the channel boundaries. In theory, maintaining the dominant discharge continuously in the channel would result in the same channel boundary configuration that would form from the fluctuations of natural hydrologic occurrences.

Drop Structure: A structure designed to have a vertical decrease in elevation at the face of the structure causing a discontinuity in the profile. Small drops may be used for fish passage, or to decrease velocities by decreasing slope and "killing" energy. Grade control structures may become drop structures if blocking a head cut.

Effective Discharge: The single discharge event which transports the largest volume of sediment. This discharge is determined by combining graphical representations of flow duration and sediment transport for each interval.

Entrainment: The incidental trapping of fish and other aquatic organisms in waters being diverted for other purposes. Sediment entrainment refers to sediment transported by flows.

Equation:

- **Empirical**: An equation developed statistically from a specific data set.
- **Analytical**: An equation which can be derived mathematically from basic physical laws of nature.
- **Regime**: An empirical equation based on a data set from a number of similar streams.

Erosion: The wearing-away of soil and rock.

Fish habitat: The aquatic environment and the immediately surrounding terrestrial environment that, combined, afford the necessary biological and physical support systems required by fish species during various life history stages.

Floodplain: That portion of a river valley, adjacent to the channel, which is built of sediments deposited during the present regimen of the stream and is covered with water when the river overflows its banks at flood stages.

Flow: (a) The movement of a stream of water and/or other mobile substances from place to place. (b) The movement of water, and the moving water itself. (c) The volume of water passing a given point per unit of time. Syn: discharge.

- **base flow**: The portion of the stream discharge that is derived from natural storage i.e., groundwater outflow and the draining of large lakes and swamps or other source outside the net rainfall that creates surface runoff; discharge sustained in a stream channel, not a result of direct runoff and without the effects of regulation, diversion, or other works of man. Also called sustaining, normal, ordinary or groundwater flow.

- **instantaneous flow**: That discharge measured at any instant in time, applied to any recommended flow term when modified by the appropriate adjective.

- **laminar flow versus turbulent flow**:

  - laminar flow: Rarely witnessed in nature. Flow devoid of the mixing phenomenon and eddies common to turbulent flow. Examples include poured honey or oil, or sheet flow over a smooth surface. That type of flow in a stream of water in which each particle moves in a direction parallel to every other particle. Normally has a Reynolds number < 5,000.

  - turbulent flow: Normal state of flow in a river. Characterized by mixing action throughout the flow field caused by eddies of varying size within the flow. Instantaneous flow velocities exhibit irregular and random fluctuations. Occurs at Reynolds Number > approximately 5,000 (or larger depending on surface roughness).

- **low flow**: The lowest discharge recorded over a specified period of time. Also called minimum flow.

- **mean flow**: The average discharge at a given stream location, usually expressed in m^3/sec, computed for the period of record by dividing the total volume of flow by the number of days, months, or years in the specified period.

- **peak flow**: The highest discharge recorded over a specified period of time. Often thought of in terms of spring snowmelt, summer, fall or winter rainy season flow. Also called maximum flow.

- **seven day/Q 10 (7 day/Q 10)**: That low flow which has occurred for seven consecutive days within a ten year period. A specific critical low flow.

- **steady flow versus unsteady flow**:

  - steady flow: flow which does not vary with time (depth or velocity). This state can be judged according to a stationary or moving observation point.

  - unsteady flow: flow changes with time.

- **subcritical flow versus supercritical flow**: Flow, at one specific energy, can be conveyed in two different conditions, slow and deep (subcritical) or shallow and fast (supercritical). The two conditions can be determined from the Froude number $(V/(gy)^{1/2})$. Most rivers and streams have subcritical flow except for short sections, with specific localized conditions. Steep, concrete lined channels can have supercritical flow. This is an important categorization for predicting flow behavior, see the specific energy diagram.

    - subcritical flow: Froude Number < 1.
    - critical flow: Froude Number = 1.
    - supercritical flow: Froude Number > 1.

- **uniform flow versus nonuniform flow:**

    - uniform flow: A flow in which the velocities are the same in both magnitude and direction from point to point. Uniform flow is possible only in a channel of constant cross-section and gradient. Assumed in rivers for many problems to simplify the analysis (one-dimensional models).

    - nonuniform flow: Flow which changes direction from section to section.

Flow Depth: The vertical distance from the water surface to the stream bed.

- **critical flow depth**: The depth for a specified discharge that requires the lowest specific energy. The depth at a Froude number of 1 which divides a subcritical flow condition from a critical flow condition.

- **normal flow depth**: The depth at uniform flow (syn. uniform depth).

- **uniform flow depth**: The depth at uniform flow (syn. normal depth). The depth calculated by the Mannings Equation.

Fluvial: Of or pertaining to rivers or produced by the action of a stream or river.

Geometric mean diameter (d_g): A measure of the central tendency of particle size composition of substrate materials sometimes used as an index of the quality of spawning gravels. Also referred to as $D_{16} * D_{84})^{1/2}$

Geomorphology: The study of the classification, description, nature, origin and development of landforms and their relationships to underlying structures, and the history of geologic changes as recorded by these surface features.

Grade Controls: Hard points in the bed of a channel which hold a set elevation in the longitudinal profile. Can be natural features such a rock outcrops or large boulder deposits, or manmade features of riprap, concrete, which resist erosion and head cut migrations.

Gradient: (a) The general slope, or rate of change in vertical elevation per unit of horizontal distance, of the water surface of a flowing stream. (b) The rate of change of any characteristic per unit of length.

Gravel: Substrate particle size between 2 and 64 mm in diameter.

Habitat type: An aggregation of land areas potentially capable of producing similar plant communities.

Herbaceous plants: Non-woody vegetation including forbs, grasses, rushes and sedges.

Hydraulic gradient: (a) The slope of the water surface. (b) The drop in pressure head per length in the direction of stream flow.

Hydraulic radius: The cross-sectional area of a stream divided by the wetted perimeter.

Hydraulics: The study of water or other liquids under all conditions of rest and motion. The science of holding and conveying water.

Hydric soil: A soil saturated long enough during the year to develop anaerobic conditions in the upper part of the soil profile.

Hydrograph: A graph showing, for a given point on a stream, the discharge, stage, velocity, or other property of water with respect to time.

Imbricated: Overlapping, as shingles or tiles on a roof.

Incipient Motion: The critical point at which a particle (sand, pebble, boulder) is balanced between stability and motion.

Incised: Cut down into or entrenched.

Lacustrine: Refers to sediments that have been deposited in a lake.

Lateral Migration: Movement of a channel perpendicular to the direction of flow.

Lithology: The physical character of rocks, especially in hand specimen and in outcrop based on such characteristics as color, mineralogical composition and grain size.

Manning's n: An empirical coefficient for computing stream bottom roughness used in determining water velocity in stream discharge calculations.

Mass Failure: Unit downslope movement of a portion of the land surface, as in creep, landslide, or slip.

Mass Wasting: The downslope movement of soil and rock material under the direct influence of gravity.

Meander Width: Measure of projected distance between outer banks of two successive meanders in a channel.

Mitigation: The act of alleviation; to render less severe.

Morphology: The study of form and structure.

Mottling: Red spots or patches in a soil profile that indicate alternating wet and dry conditions of a fluctuating water table.

Outcrop: That part of a geologic formation or structure that appears at the surface of the earth; also, bedrock that is covered by surficial deposits such as alluvium.

Passive revegetation: A revegetation strategy allowing natural establishment of vegetation and involving no installation of plant materials.

Pedogenic: Refers to the processes of soil formation.

Permissible Velocity: The maximum mean velocity of a channel that will not cause erosion of the channel boundary.

Phreatophyte: A deep rooted plant that obtains its water from the water table or the soil layer just above it (i.e., cottonwoods plus many willows).

Pioneer species: Species that colonize bare areas (e.g., gravel bars) where there is little or no competition from other species.

Planform: The configuration of a river system viewed from above.

Pleistocene: The earlier of the two epochs that comprise the Quaternary period, the latter of which is the Holocene or Recent epoch.

Point Bar: The depositional surface on the inside of a bendway composed of coarser grained accreted sediments.

Pool-riffle ratio: The ratio of the surface area or length of pools to the surface area or length of riffles in a given stream reach, frequently expressed as the relative percentage of each category.

Profile: A graphical presentation of elevation vs. distance, as in channel cross-sections and longitudinal sections. In open channel hydraulics, it is a plot of water surface elevation against channel distance.

Quaternary: Geologic period that comprises the latter part of the Cenozoic era (approximately the last 2 m. years).

Radius of Curvature: The measure of the curvature of a bendway. Radius arm can end at center of stream or outer edge of river depending on application. Angle is measured to points of tangency upstream and downstream of the bend.

Reach: (a) Any specified length of stream. (b) A relatively homogeneous section of a stream having a repetitious sequence of physical characteristics and habitat types. (c) A regime of hydraulic units whose overall profile is different from another reach.

- representative reach: A length of stream which represents a large section of the stream with respect to area, depth, discharge, and slope.

Recurrence interval: Expected or observed time intervals between hydrological events of a particular magnitude described by stochastic or probabilistic models (log-log plots).

Revetment: A blanket of material covering a channel bank to prevent erosion. Normally composed of rock riprap, but can be constructed from poured concrete, preformed concrete blocks, or scrap materials such as broken paving or car bodies.

Rhizome: A creeping underground stem. A desirable quality for riparian revegetation species.

Rill: One of a set of well-defined subparallel channels varying in size with the erodibility of the soil. Generally these channels are only a few inches wide and deep.

Riparian: Pertaining to or situated on the bank of a river.

Riparian Vegetation: Vegetation growing on or near the banks of a stream or body of water on soils that exhibit some wetness characteristics during some portion of the growing season.

Riprap: A layer of large, durable materials (usually rock but sometimes car bodies, broken concrete, etc.) used to protect a stream bank from erosion. May also refer to the materials themselves or to a gradation of large rock. Syn. revetment.

Root mass: A living assemblage of plant roots and associated soil.

Roughness coefficient: See Manning's n.

Run: An area of swiftly flowing water, without surface agitation or waves, which approximates uniform flow and in which the slope of the water surface is roughly parallel to the overall gradient of the stream reach.

Saturated: In soils, a condition where water has filled soil pores, replacing oxygen.

Scour: The process of removal of material from the bed or banks of a channel through the erosive action of flowing water.

- **bend:** Erosion produced by the roller or spiral motion of secondary flow currents in the bend of a channel.

- **confluence**: The erosion which occurs when two branches of a river meet.

- **contraction (or constriction)**: Erosion which occurs in a confined reach of river as a result of natural rock features or manmade walls and structures.

- **jet**: A concentrated stream of flow striking an erosive surface. An example is a culvert outlet with flows impacting an adjacent bank.

- **local**: Scour resulting from an obstruction in the flow field which produces roller currents that erode in a horseshoe pattern when observed in plan view.

- **long term**: Scour resulting from larger scale geomorphic trends. Examples include reduced sediment input to the system resulting from urban development, mining operations, or the construction of systems upstream to capture sediment.

- **sill/drop/weir**: Water dropping a vertical distance creates vortices (roller flow patterns) which erode the base of the drop.

Scroll Bars: Concentric sandy ridges that form on the upper point bar surface at the approximate elevation of the bankfull flow of the river. They record the lateral migration of the bend.

Section: One cross section of a stream normally sliced vertical and perpendicular to the direction of flow (syn. cross-section).

Sediment: Fragmental material that originates from weathering of rocks and decomposition of organic material that is transported by, suspended in, and eventually deposited by water or air, or is accumulated in beds by other natural phenomena.

Sediment discharge: The mass or volume of sediment (usually mass) passing a stream transect in a unit of time. The term may be qualified, for example, as suspended-sediment discharge, bedload discharge, or total-sediment discharge, usually expressed as tons per day.

Sediment load: A general term that refers to sediment moved by a stream, whether in suspension (suspended load) or at the bottom (bedload). It is not synonymous with either discharge or concentration. (see bedload).

Sediment Transport Capacity: The capability of a channel to carry a given volume of sediment based on local hydraulic and geometric parameters.

Shear Stress: syn. shear force. A measure of the erosive force acting on the channel boundary, with the force acting parallel to the area. It is given as force per unit area (lb/ft^2). In a channel, shear stress is created by water flowing parallel to the boundaries of the channel.

- **bed shear stress.** The value given by the equation $\tau = \gamma d S_e$, also the shear value calculated by the HEC-RAS program.
- **bank shear stress.** The shear stress acting on the banks is normally estimated as a function of the bed shear stress.

Sinuosity: The measure of how straight or curved a channel is. It is the ratio of its actual channel length to the straight-line distance down valley. Channels with sinuosities of 1.5 or more are called "meandering."

Soil texture: The percentage of sand, silt, and clay in a soil.

Stand: A plant community relatively uniform in composition, structure, and habitual condition.

Stone Toe: The foundation of a channel bank constructed of a gradation of rock.

Stratigraphy: The arrangement of sedimentary layers or units based on geographic position and chronological order of sequence.

Stream: A natural water course containing flowing water, at least part of the year, supporting a community of plants and animals within the stream channel and the riparian vegetation zone. Streams in natural channels may be classified as follows:

a) Relation to time:

- **ephemeral**: One that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

- **intermittent or seasonal**: One in contact with the groundwater table that flows only at certain times of the year as when the ground water table is high and/or when it receives water from springs or from some surface source such as melting snow in mountainous areas. It ceases to flow above the stream bed when losses from evaporation or seepage exceed the available streamflow.

- **perennial**: One that flows continuously throughout the year. Syn: permanent stream.

b) Other:

- **incised**: A stream that has, through degradation, cut its channel into the bed of the valley.

Streambed: The substrate plane, bounded by the stream banks, over which the water column moves. Also called stream bottom.

Stream capacity: (a) Total volume of water that a stream can carry within the normal high water channel. (b) The maximum sediment load a stream can carry.

Stream classification: Various systems of grouping or identifying streams possessing similar features according to geomorphic structure (e.g., gradient), water source (e.g., spring creek), associated biota (e.g., trout zone) or other characteristics.

Stream power: The rate of doing work, or a measure of the energy available for moving rock, sediment particles, or woody or other debris in the stream channel, as determined by discharge, water surface slope, and the specific weight of water.

Subarmour: Those sediments lying below and protected from erosion by an overlying or surficial armor layer such as gravel or cobbles.

Substrate: The mineral and/or organic material that forms the bed of the stream.

Succession: The progressive change in plant communities over time, toward a stable one. Primary succession begins on a bare surface not previously occupied by plants, such as a recently deposited gravel bar.

Suspended load: The portion of the total sediment load that moves in suspension, free from contact with the streambed, and is made up of particles having such density or grain size as to permit movement disassociated from the streambed. Density and grain size vary according to the amount of turbulence. Only unusually swift streams are turbulent enough to lift particles larger than medium-sized sand from their beds. See bed load.

Suspended sediment: Those sediments that are part of the total stream load that is carried for a considerable period of time in suspension, free from contact with the stream bed; it consists mainly of clay and silt.

Terrace: A relatively level bench or steplike surface breaking the continuity of a slope. In river systems, an old alluvial plain bordering a river that is seldom subject to overflow.

Thalweg: The path or thread of main flow, usually follows the deepest path in the channel.

Tractive Force: The name for shear stress specific to river channels. The term shear stress is universal and can be applied to everything from structural analysis to the forces involved in spreading peanut butter. Tractive force is shear stress acting on stream banks.

Tubeling: A nursery-grown containerized plant grown in a narrow but deep container.

Uplands: Areas that ordinarily support plants not adapted to continually wet saturated conditions.

Velocity: The time rate of motion; the distance traveled by a point in the flow divided by the time required to travel that distance.

- **average approach flow velocity**: Mean cross-sectional velocity directly upstream of the point of interest.
- **critical velocity**: The velocity in a channel at which flow changes from a subcritical flow condition to a critical flow condition.
- **mean column velocity**: The average velocity of the water measured on an imaginary vertical line at any point in a stream. A measurement at 60% of the depth, measured from the surface, closely approximates the average velocity for the water column. In water greater than 76 cm in depth, the average of measurements made at 20% and 80% of the depth approximates the mean column velocity.
- **mean cross-sectional velocity**: Represents the mean velocity of water flowing in a channel at a given cross-section. It is equal to the discharge divided by the cross-section area of the cross section.
- **profile**: A curve representing the velocity of flow along a given line.

- **thalweg velocity**: The mean column velocity at the thalweg.

Vertical Accretion: Growth of a sedimentary deposit by upward deposition.

Water Year: See Climatic year.

Weir: (a) A levee, dam, embankment, or other barrier across or bordering a stream, over which the flow of water is measured or regulated. (b) A barrier constructed across a stream to divert fish into a trap. (c) a dam (usually small) in a stream to raise the water level or divert its flow.

Wetland indicator status: According to Reed (1988), the estimated probability of a species occurring in a wetland versus a nonwetland.

Wetted perimeter The length of the wetted contact between a stream of flowing water and the stream bottom in a vertical plane at right angles to the direction of flow.

Wetted width: The width of the water surface measured at right angles to the direction of flow and at a specific discharge. Widths of multiple channels are summed to represent total wetted width.

Wolman Count: A fixed interval method of field sampling of the coarse bed and bar materials using a template that is calibrated in the same intervals as standard laboratory sieves (from 2 to 256 millimeters).

Woody Debris: Logs, branches, roots of trees and large shrubs in channels.

Woody plants: Trees and shrubs.