Chapter 7
River Processes and Restoration

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by

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7.1 Introduction

River channels and flood plains convey water, transport sediment, and often support complex ecosystems that include aquatic and terrestrial plants, fish, and wildlife. Rivers are important resources that provide environmental, cultural, and economic benefits including municipal water use, irrigation, hydropower, navigation, fishing, and recreation. In achieving these benefits, the natural processes of the river and the ability of natural ecosystems to function over the long term are often impacted. This can result in unanticipated consequences, such as the loss of aquatic and terrestrial habitat for fish and wildlife.

River channels and flood plains convey runoff from rainfall and snowmelt. They can temporarily delay floodwaters, thereby reducing flood peaks. The processes of sediment erosion, transport, and deposition may cause local and system-wide adjustments in the bed and banks of the river channel, including the migration of a river channel across the flood plain. In a natural setting, undisturbed by anthropomorphic impacts or cataclysmic events, the river is dynamic and changes occur over time as a result of these sediment processes. However, when viewed over the long term, these changes tend to fluctuate about an equilibrium condition, known as dynamic equilibrium. Disturbances to the river corridor often affect these sediment processes, and the channel may become unstable (i.e. no longer in a state of dynamic equilibrium). With time, the disturbed channel may achieve a new state of dynamic equilibrium, but viable water management activities or appropriate aquatic habitat for fish and wildlife may not be sustainable during this period of transition. Disturbances to rivers and streams can be caused by dams, water diversions, levees, roads, bridges, bank protection, removal of vegetation and woody debris, logging, grazing, gravel mining, urbanization, and recreation.

Although river restoration can mean different things to different people, in this manual, restoration is defined as the full or partial restoration of natural processes and dynamic equilibrium. Natural processes in a river channel below a dam might be restored by modifying dam releases to replicate portions of the natural hydrologic cycle that are in proportion with the sediment supplies to the downstream river channel. In the case of a river with flood-control levees, the levees might be set back or removed to restore the connection between the main channel and flood plain. The challenge for restoration planning and design is to ensure that the river channel and flood plains are capable of conveying water, transporting sediment and large woody debris (if present), and supporting aquatic and terrestrial ecosystems in a long-term dynamic equilibrium.

The recent publication, *Stream Corridor Restoration: Principles, Processes, and Practices* (Federal Interagency Stream Restoration Working Group, 1998), provides a comprehensive discussion of the physical, chemical, and biological processes related to stream corridors and describes the aspects of restoration planning and design. Another recent publication, *Channel Restoration Design for Meandering Rivers* (Soar and Thorne, 2001), describes the analysis and restoration design procedures for meandering rivers.

This chapter of the *Erosion and Sedimentation Manual* focuses on physical river processes and sediment management aspects of river restoration. Accordingly, this chapter avoids the discussion of the legal and institutional policy issues. In Section 7.2, the technique of using a conceptual model to formulate hypotheses, determine analysis methods, and design data collection programs is described. Section 7.3 discusses potential data collection activities and the application of various analytical and numerical modeling tools, along with their applicability to various sediment management questions. Section 7.4 provides some management considerations for choosing a sediment restoration option, various techniques that have been implemented and their applicability to sediment issues, and a discussion of how adaptive management techniques can be incorporated into restoration projects.

7.2 Conceptual Model

Restoration projects begin with the resource management goals and objectives, such as improving riparian vegetation, fish habitat, wildlife habitat, water quality, or aesthetics. For some projects, the goals and objectives may be to limit or stop bank erosion for a reach where human impacts have accelerated the natural rates of channel migration. The goals and objectives help to determine the reasonable range of restoration options. The range of options, in turn, helps to determine the required analysis methods and the data collection needs.

Defining the restoration goals and objectives can be a difficult policy process. There are often many resource management agencies, landowners, and other special interest groups involved, and each party has different management objectives. There may also be conflicting interpretations of the processes affecting the river and the range of feasible restoration options that can be applied.

Understanding the key processes that have affected, and continue to affect, the river corridor is a prerequisite to river restoration projects. The formulation of a conceptual model can help the investigators, resource management agencies, landowners, and other interested groups begin to think about and understand the linked processes that affect the river corridor. This understanding can help refine the resource management goals and objectives and help determine the range of feasible restoration options.

The formulation of a conceptual model is a continuing and dynamic process that occurs throughout the study. The conceptual model can continue to be refined after project implementation as part of an adaptive management process (see Section 7.4.6). Initially, the conceptual model may be nothing more than a linked set of hypotheses that need to be tested, but these hypotheses will help determine the data collection and analysis needs to get the project started.

The conceptual model may incorporate different temporal and spatial scales, depending on the processes affecting the study reach. River processes can be driven by recent geologic processes that have evolved over thousands or tens of thousands of years. The understanding of geologic processes, such as landslides, debris flows, and uplift may require a temporal scale of centuries and a spatial scale that includes hundreds of square miles. The conceptual model should also consider the temporal scale of the disturbance to the river reach with a corresponding spatial scale that includes the river reach of interest and the distance to the source of possible disturbance. For hydrologic processes, a spatial area of the upstream watershed should be considered in combination with a temporal scale of several decades. However, the processes associated with individual floods, such as the downstream translation of discharge waves, river channel erosion, migration, and sediment deposition, would require a time scale of minutes, hours, or days, and a spatial scale measured in smaller increments of the watershed, possibly feet or miles. Unlike numerical models, a conceptual model can easily accommodate different time and space scales for different processes.

The first steps in developing a conceptual model include a literature review of technical studies in the area; an initial review of available maps, aerial photographs, and stream gaging data, and a field reconnaissance trip to the study area. The initial conceptual model will have some uncertainty, but it provides a tool to formulate an appropriate study plan including data collection and analysis activities, to help reduce uncertainty and answer study questions. A variety of data collection and analyses tools that can be used to test and improve the conceptual model are discussed in the next section.

7.3 Data Collection, Analytical, and Numerical Modeling Tools

The choice of data collection and analysis methods needs to be customized to the requirements of the project, since every project is unique. The following discussion provides a range of data collection activities and analytical and numerical tools that can be used in a restoration project, and the potential benefit of each in understanding the role of sediment processes in the river system being studied. Depending on the size of the project and resources available, analyses can range from simple computations to a multi-dimensional, customized model to analyze various restoration options. When identifying tasks for a restoration project, the objective should be to choose a suite of integrated, multi-discipline analyses that address management questions and research hypotheses posed in the conceptual model.

7.3.1 Data Collection Activities

The types of data collection activities should be driven by the analytical and numerical analyses that will be accomplished as part of the restoration project and by future monitoring needs. Some of the more typical examples of data collection activities that can be utilized to support several types of analyses are listed below:

- The collection of historic maps, aerial photographs, and ground photographs is essential for understanding the history of channel migration and land use over the last several decades. Future trends in channel migration are often predicted by examination of historic trends.

- Aerial field reconnaissance can be a very helpful way of viewing the watershed, especially in areas of dense forest or rugged terrain.

- Topographic surveys of the river channel, flood plains, terraces, and high water marks describe the relationship between riverflow and water surface elevation (stage-discharge rating curves). This relationship helps determine the bankfull discharge and the discharge required to inundate terraces at the flood plain boundaries. Topographic survey data are also essential for the numerical modeling of hydraulic and sediment transport processes.

    - Ground survey methods include using total stations, real-time kinematic global positioning system (RTK GPS) instruments, and depth sounders from boats. Aerial survey methods include photogrammetry and light detection and ranging (LIDAR) systems. Depth sounders from boats work best for river channels that are too deep to wade. RTK GPS can be used to track the horizontal and vertical coordinates of a moving boat. In 1 week, a raft equipped with a depth sounder and RTK GPS was used by the authors to survey 30 miles of the Hoh River near Forks, Washington (Piety et al., 2003). In river reaches where satellite coverage may be limited by mountains, canyon walls, or riparian forests, robotic total stations can be used to track the position of a moving boat over a distance of approximately 1,000 feet. This method was used in a 1-mile canyon reach of the Rouge River below Savage Rapids Dam, near Grants Pass, Oregon, and also within a 5-mile reach of the Teton River Canyon near Driggs, Idaho (Bountry and Randle, 2001; Randle et al., 2000).

    - The ortho-rectification of aerial photographs, using stereo pairs, can produce digital elevation models (grids or surfaces) and contour maps (photogrammetry) of the river corridor and also allow the rectification of historic aerial photographs. The grid size or contour interval that can be produced from photogrammetry depends on the ground survey control and the altitude at which the photographs are taken (see "Geospatial Positioning Accuracy Standards," *Part 3: National Standard for Spatial Data Accuracy,* by Federal Geographic Data Committee, 1998 and "Using the National Standard for Spatial Data Accuracy to measure and report geographic data quality," in *Positional Accuracy Handbook* by Land Management Information Center Minnesota Planning, 1999). The more precise the survey control and the lower the photograph altitude, the smaller the contour interval that can be achieved. Proper survey control depends on the use of photograph control panels or painted lines on paved surfaces. Where vegetation is present, photogrammetry is most effective when the base aerial photography is taken during the winter when deciduous trees lose their leaves. Photogrammetry cannot produce accurate ground elevations in densely forested areas, especially in conifer forests. Ground surveys using total stations along cleared lines would be necessary for areas of dense vegetation. Aerial photography taken at low flows is best for developing topography of exposed riverbed topography, however, aerial photographs taken during floods can also be useful because it directly measures the areas of inundation. Although photogrammetry cannot produce reliable elevations below water, the data above water can be combined with the channel bottom data surveyed by boat. The channel bottom survey should preferably be measured at a higher flow level than when aerial photographs are taken, so the data overlaps. Reclamation surveyed a 12-mile reach of the Snake River near Fort Hall, Idaho, during April 2000 using a combination of photogrammetry and a channel bottom survey by boat (Bureau of Reclamation, 2001). Photogrammetry was used for the gravel bars exposed above water, the flood plains, and terraces. A raft equipped with a depth sounder and RTK GPS was used to survey the wetted river channel. The data was then combined to make a continuous digital elevation model of the study area.

  - LIDAR surveys can provide useful topography data in forested areas. This method transmits light from an aircraft to the ground surface to measure elevations. The method requires that at least some of the light beams reach the forest floor and reflect back to the aircraft. Therefore, a LIDAR survey works best during the winter months when deciduous trees lose their leaves. Ortho-rectified aerial photographs collected simultaneously with the LIDAR data are very useful for processing the LIDAR data and for interpreting the topographic data produced from LIDAR surveys. Reclamation has used LIDAR to survey the forested flood plains and exposed gravel bars along the Elwha and Quinault Rivers of the Olympic Peninsula in Washington. The LIDAR survey of the Elwha River revealed the existence of a channel through a forested terrace that had not been identified before. A subsequent field inspection later verified the existence of this channel. LIDAR data on the Quinault River allowed a fairly quick identification of terrace surfaces and historical channels throughout the valley floor that would not have been detectable from aerial photography alone. Although the cost of LIDAR surveys may appear high, the survey can provide ground elevations in large forested areas that would be time consuming and expensive to survey through ground-based methods.

- Particle size gradation measurements of the bed and bank materials are necessary for computations of sediment transport capacity and the assessment of channel stability. Also, the comparison of bed-material particle size with longitudinal distance along the river can help determine where the sediment transport capacity of the river changes or identify additional sources of sediment from tributaries. Pebble counts (Bunte and Abt, 2001) can be used to measure the particle size distribution of gravels and coarser material exposed on the surface of the channel bed. The particle size distribution of surface and subsurface layers within a unit area (e.g., 1 m^2, 1 yd^2) can also be measured for cobbles, gravels, and sands by sieving and weighing in the field. Ground-based photography methods can also be used to quickly record the surface particles at many different locations. If a scale is placed in the photograph, the particle size distributions can then be measured from the photographs using commercially available software.

- Measurements along river and terrace banks, such as height, slope, material composition, and vegetation root density can be used to assess bank stability.

- Soil profiles and radiocarbon analysis of charcoal material in terrace deposits can be used to determine the minimum age of the deposits. This information is useful for defining the flood plain and channel migration zone boundaries, the frequency of large and rare floods, and the minimum age that the terrace was abandoned by the active river channel.

- Measurements of large woody debris (location, size, and type of wood) that are present along the active channel and flood plains are useful for assessing the rates and locations of lateral channel migration, the abundance of aquatic habitat, and the amount of additional roughness present in the channel (Abbe, 2000). Large and stable logjams can create fish habitat, protect riverbanks and islands from erosion, and slow the rates of lateral channel migration.

- Investigations of sediment sources to the study reach will help determine the primary processes and timing of sediment delivery. For example, sediment may be primarily supplied from certain portions of the upstream watershed, from landslides, from tributary debris flows, and from channel bank and bed erosion.

- Stream gaging of river stage and water discharge, suspended sediment load, and bedload is needed to quantify streamflow and sediment transport rates and to calibrate numerical models. Historical gaging measurements often also document channel geometry and velocity during a range of flows. Measurement of water temperature and turbidity levels may also be useful where aquatic habitat is of primary concern.

- Measurement of flow velocity (direction and magnitude) in the river channel can help provide information to calibrate numerical or physical models, provide an indication of where depositional areas exist, and show the presence of secondary currents that may initiate bank erosion.

7.3.2 Geomorphic Processes

A geomorphic analysis provides the context to help understand the river channel planform, historic channel paths and rates of migration, interactions with flood plains and terraces, and sediment sources and sinks. The analysis helps to identify upstream and downstream influences, geologic controls along the study reach, and human actions that have affected the natural processes. The analysis assists in identifying the cause(s) and magnitude of the disturbance to be restored, potentially useful methods for restoration, and likely channel response to restoration activities.

An example using the Hoh River near Forks, Washington, illustrates many of the processes occurring in and around a river. Figure 7.1 shows a composite cross section of the Hoh River valley, including the river channel, flood plain, and terraces. Because the relative amounts of water, sediment, and woody debris are continually changing, the channels and flood plain are continually adjusting to the variable supplies of these three components. Response to the changes may vary with time and location along the river, depending upon local conditions and the

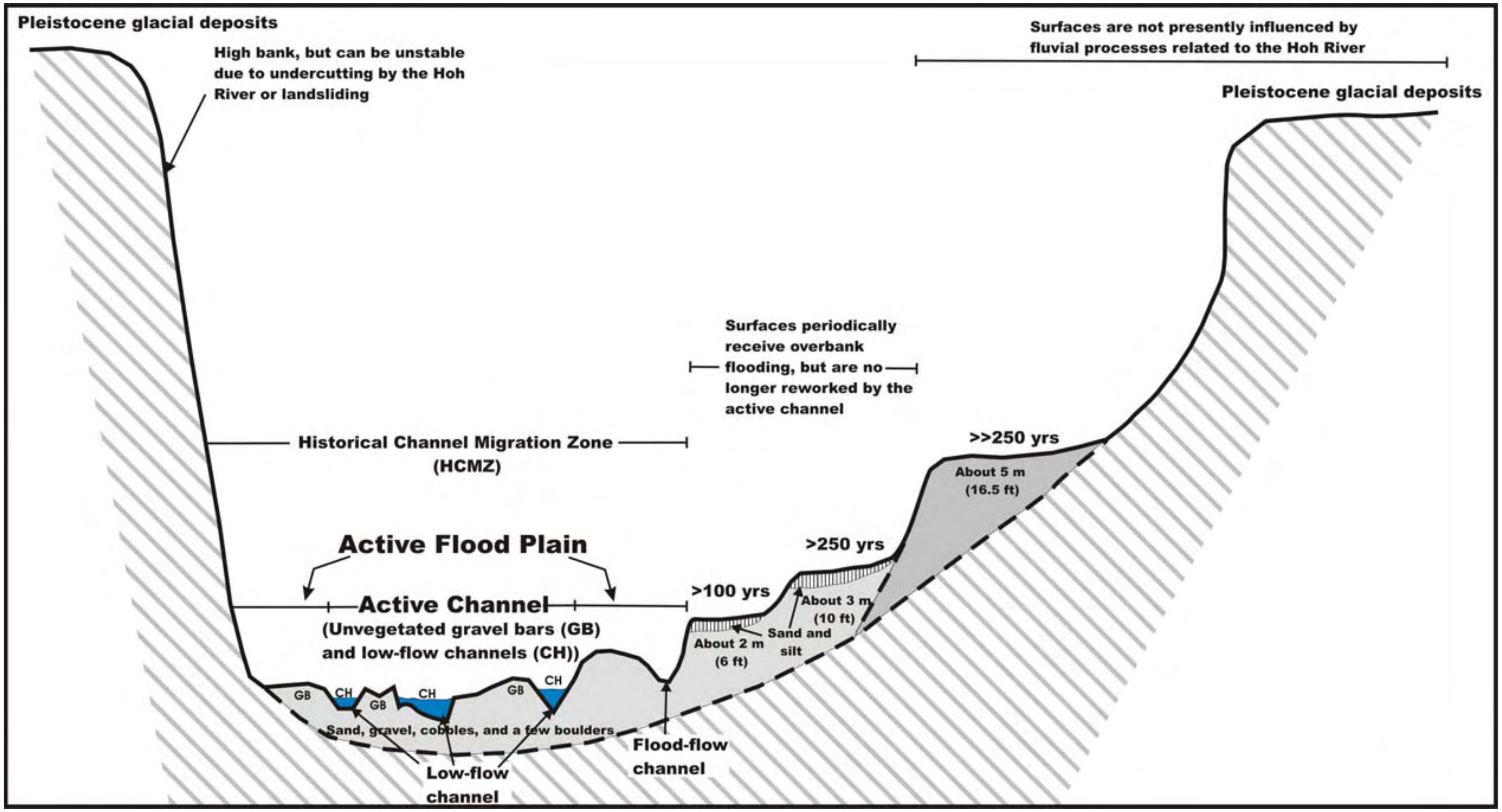

Figure 7.1. Generalized schematic cross section across the Hoh River valley, showing the relationships between the active channel, flood levels, and terraces

frequency of flooding. Water, sediment, and woody debris may move longitudinally down the valley, but alteration in these components may also result in vertical downcutting or aggradation, or in lateral erosion or deposition. In this way, natural river channels are dynamic and are subject to change over time, especially as bankfull and higher flows pass through the channel and rework sediment and woody debris.

The terraces in Figure 7.1 are numbered from T2 to T5 on the basis of their relative age and positions above the active river channel. This sketch is a composite of many sites along the river, so that a single locality may have fewer or more terraces. The estimated terrace ages are from Fonda (1974) and Swanson and Lienkaemper (1982). The ages are based primarily on the ages of trees growing on the terraces and reflect the time when the terraces became stable enough to support trees.

The active channel includes the low-flow channels and intervening and adjacent sand or gravel bars as shown in Figure 7.1. The bars are often unvegetated, but they may be sparsely covered with seedlings, grasses, and shrubs. The higher bars are often covered with finer sediment. This main channel may be straight or meandering in planform. The channel alignment and width depends on the rate of riverflow and sediment supplied from upstream. In an alluvial river reach, the channel bed and banks are composed of sand, gravel, and cobble-sized sediments and are not constrained by bedrock. In these alluvial river reaches, the channel width, depth, and longitudinal alignment will adjust over time so that the upstream supply rate of water and sediment can be conveyed through the reach without long-term erosion or deposition. The hydraulic capacity of the river to transport sediment increases primarily with the longitudinal slope of the river and the rate of riverflow, which includes an increase in flow velocity and depth. The longitudinal slope of the river is limited by the valley slope (straight channel) but can be less if the river meanders back and forth across the river valley.

If the upstream sediment supply rate is greater than the hydraulic transport capacity, then sediment can deposit in the river channel and the resulting alignment will tend to follow a straighter pattern. If the river channel alignment is already straight, additional sediment deposits will result in a braided river with multiple channels. If the upstream sediment supply rate is less than the sediment transport capacity, then the channel bed and banks can erode and the resulting alignment will tend to follow a more meandering pattern. If coarse particles remain on the riverbed while finer particles erode, then eventually a coarse layer of particles will armor the riverbed and limit channel bed incision. However, a subsequent flood can later erode the armor layer if there is enough sediment transport capacity to move the larger-sized particles.

When straight, the river channel may have the potential to locally undercut and erode banks on either side of the river, and it can locally deposit sediment during high flows in the form of mid-channel or longitudinal bars that run parallel with the river channel. When meandering, the river will typically erode the outside bank of the meander bend while maintaining enough channel width to convey high flows by depositing sediment along the inside of the bend. Sediment deposits on the inside of bends are referred to as point bars. This continual process of erosion along the outside bank of a meander bend and deposition along the inside bank allows the river channel to migrate laterally across the valley and downstream along the valley, while building and reworking the flood plain. The deposition of woody debris on gravel bars and subsequent formation of logjams also play an integral role in the occurrence of channel changes by creating multiple channel paths and either causing or mediating avulsions (Collins and Montgomery, 2002). Large woody debris also increases the channel roughness. If logjams are large enough to span the river channel, they can locally increase the river stage, which creates waterfalls over the logjams, short scour pools immediately downstream, and longer pools upstream. The upstream pools and the increased roughness can reduce the sediment transport capacity of the river channel.

In most wide valleys with a flat floor, one can expect that the river has been in many positions across the valley floor at some point in the past (Leopold et al., 1964 and Leopold, 1994). Terraces within the valley are remnants of old flood plains and consist of old channel deposits of gravel and sand. A change in the relative proportion of water and sediment resulted in incision into these channel deposits, which left them exposed above the new active channel and flood plain (Figure 7.1). The old channel bed and flood plain, now a terrace, may still receive some water during higher flows, and the old channel deposits are often covered by fine sand and silt. If incision continues, the terrace may eventually be high enough above the level of the channel so that frequent floodflows no longer reach its surface. In this way, the terrace surfaces slowly stabilize, vegetation establishes, and soils begin to form. Higher terraces are often progressively older.

The historic channel migration zone boundary is defined by the area of the existing active channels and flood plains. The active river channel represents the low-flow river channel and sand/gravel bars that are frequently reworked during floods. The active flood plain includes areas adjacent to the active channel that contain side channels, secondary or flood plain channels, and low-elevation, vegetated surfaces that are frequently inundated by floods with recurrence intervals in the range of 1.5 to 5 years. The area outside of the historic channel migration zone boundary can still be inundated, but larger floods are required to overtop the terrace banks that form this boundary. The area within the historic channel migration zone is dynamic and continually being reworked and changing during floods. It represents the area where the majority of coarse sediment (sand, gravel, and cobble) and woody debris is either currently being transported (active river channel) or has been deposited.

The historic channel migration zone can be bounded by terraces, glacial deposits (till, outwash, lacustrine sediments), alluvial fans, bedrock, or bank protection (riprap, engineered logjams, bridge abutments, levees, road embankments). In some locations, future channel changes will expand the historic channel migration zone boundary where the boundary consists of erodible material, but this process is slow for stable systems. Significant long-term changes in river discharge and sediment supply (either natural or human caused) could cause major aggradation or incision and redefine the channel migration zone.

Information from several sources such as geology, climate, topography, soils, vegetation, channel morphology, and a chronology of disturbances both natural and anthropogenic is combined in a geomorphic analysis (Thorne, 2002). Processes and channel changes can be investigated at the local, reach, and watershed scales. Aerial photography and reconnaissance are excellent tools to view the larger scale attributes of the river system. Historical data including previous studies, maps, agricultural reports, and photographs can provide invaluable information about the river system over time. Time scales may also vary in an investigation, from a single year to decades or centuries. Geomorphic changes can occur over years to millions of years, but a stream restoration project generally considers the results of such changes in terms of years to decades (Federal Interagency Stream Restoration Working Group, 1998).

7.3.2.1 Geology

With respect to a river, geology can be thought of as providing the general setting for the movement of water and sediment. The characteristics of the geology are dependent on the composition and structure of the earth's crust. In particular, the lateral and vertical extent of bedrock potentially limits the channel position over time. A geomorphic analysis should include a discussion of the general lithology and structure of the study site, particularly with regard to its effect on the river. Structure is the shape and position of rock units and their relationships to each other. It includes faults, joints, fold patterns, layering, etc. Tectonic plate movement is a prime force in determining structure. Uplift of the underlying bedrock is often a cause of channel incision. As the general elevation of the land increases, the river may erode the bed to maintain its slope (Schumm, 2000). An extreme example is the Grand Canyon of Arizona.

Lithology is the chemical and mineralogical composition, texture, and internal strength of the rock. Texture can be described as unconsolidated, indurated (hard), fractured, or solid. Solid or indurated rock often provides a control point for bed elevation and slope. The amount of time it acts as a control will be influenced by the lithology. For example, limestone may be eroded faster than basalt in a wet climate. Erodibility, porosity, and permeability are characteristics defined by both structure and lithology. Spatial variability of these characteristics should be noted. Textural distribution of unconsolidated sediment can be very significant. Larger-sized sediment, such as cobbles or boulders, may armor the channel at the mouth of a tributary and act as a control point similar to solid rock.

7.3.2.2 Climate

The atmospheric aspects of the basin include such things as precipitation intensity, duration and frequency, temperature, and year-to-year and seasonal variability. Climate can be thought of as the meteorological aspects that influence the hydrology. Long-term climate changes can cause glaciers to advance and retreat and sea level to fall and rise. These changes can have profound effects on river systems that can include degradation and aggradation.

Short-term climate fluctuations of 3 to 10 years can be detected through analysis of instrument records of precipitation and flow, and through extensions of these records based on paleo techniques. The science of tree-ring analysis has considerably extended the record of climate based on instrument measurements. Instrumented data are available back to approximately 1895; however, the paleo technique of dating tree rings provides information back to the 1600's or 1700's in the Western U.S., while other paleo techniques can extend the record back a thousand years or more. Tree-ring data have been used to extend the period of record for temperature measurements, the Palmer Drought Severity Indices (PDSI), and for some hydrological records of streamflow. The PDSI is a drought model derived by Palmer (1965) that is computed from temperature and precipitation data to provide a measure of climatic stress on crops and water supplies

Dates and duration of climactic fluctuations (for example documenting a drought or wet period) are often used to identify the cause of changes in river behavior. The middle Rio Grande in central New Mexico has shown direct correlation between periods of channel narrowing and drought (Bauer and Makar, 2003). The channel narrowed through vegetation colonization and the attachment of bars and islands to the channel banks that were formed during the drier periods between the mid-1940's and the mid-1970's. Peak flows were not high enough to scour new vegetation, which then became established and resistant to removal. Later increases in flows tended to erode the channel bed rather than the banks in many locations. Current research topics that relate to river channels include the influence of the El Nino Southern Oscillation on long-term weather patterns.

7.3.2.3 Topography

Topography is primarily the relief, aspect, and elevation of a river basin. Relief is the amount of change in elevation, which has an influence on channel slope or gradient, runoff, sediment storage, and delivery to the river. Aspect and general site elevation, which may be less influential, affect vegetation type and growth, sediment deposition and storage, soil development, and microclimates.

7.3.2.4 Soils

The development of soils is influenced by several factors, including geology, climate and topography. Soils strongly influence runoff and the type of vegetation. Soils may control other aspects of the fluvial system such as water quality, slope and bank stability, and sediment supply. Soil formation is also commonly used to estimate the age of particular landforms (Birkeland, 1999). Soil profiles may therefore be useful in determining the age of terraces, rates of channel migration, and landscape stability or instability, such as periods of deposition and erosion.

7.3.2.5 Vegetation

Types of vegetation are largely determined by the four previously listed factors and may, in turn, influence the state of those factors. The age and successional stage of vegetation can be used to establish the age of fluvial deposits and landforms. The stability of banks can be strongly influenced by root structure and extent. Lateral migration of the river channel across the flood plain is often restricted by vegetation. Large woody debris (snags and logjams) can also be a controlling factor of the channel morphology.

7.3.2.6 Channel Morphology

Channel morphology is described by the shape, slope, and pattern of the channel and includes the flood plain and terraces. The shape of a natural channel is irregular, but can be represented by several variables, including the channel width at bankfull discharge, average and maximum depth, channel side or bank slope, cross-sectional area, and wetted perimeter. Channel bank slope is frequently different for each riverbank location and can be estimated by the slope of a line from the point defining channel top width in a bankfull stage to the point defining channel bottom width at a low-flow stage. The steepest section of bank slope can also be measured to assess bank stability. The hydraulic radius (cross-sectional channel area divided by the wetted perimeter) and the width-to-depth ratio are two other commonly used variables that are derived from the measured variables. Channel shape may also include bed forms such as ripples, dunes, pebble clusters, and point bars (Knighton, 1998). Flood plain width and terrace height are useful measures to help identify the channel migration zone. Dimensionless ratios between these parameters are often used as indicators to compare channel properties between reaches and to reference reaches.

Slope is the longitudinal gradient of the river. Within the constraints of the longitudinal valley slope and bedrock outcrops along the valley walls, the river channel slope is a function of the riverflow and sediment load. The river channel slope, or longitudinal profile, can be defined by measuring elevations along the channel thalweg (lowest point in the river cross section), the average riverbed elevation, or the water surface elevation at some reference discharge (e.g., bankfull discharge). Although the river slope can be locally steep at riffles and rapids, the average slope cannot be steeper than the valley slope. Reach-scale changes in riverbed material, sediment load, or discharge can be the major causes of reach-scale variations in profile, while factors such as geology, hydrology, and watershed size influence the shape of the generally concave bed profile on a basin scale (decreasing slope with distance downstream).

The sequence of riffles and pools is another aspect of channel form. Pool and riffle sequences are found in most river patterns and result from a combination of scour and deposition. The longitudinal spacing of pools and riffles is usually fairly regular. The channel thalweg moves from side to side across the channel. The deepest pool is usually found at the apex of the curve and along the outside of the meander bend. The shallow, coarser-grained riffle is usually found at the crossing point, which is the tangent between two meander bends. The sequence of pools and riffles may be unsymmetrical or skewed due to local factors. Leopold (1994) found that, for channels of all sizes, there is a remarkable relationship among the meander wavelength, channel width, and the radius of curvature. The meander wavelength is nearly always between 10 and 14 times the channel width, with an average of 11 times the channel width. The radius of curvature for the central portion of the meander curve averages about one-fifth of the meander wavelength. This means that the radius of curvature is about 2.3 times the channel width.

River planform has traditionally been divided into three classes: straight, meandering, and braided (Leopold and Wolman, 1957), with meandering being the most common planform type (Leopold, 1994). Schumm (1985) defined 14 patterns based on the type and amount of sediment load moving through the river, single or multi-channel character, and sinuosity. Schumm also assigned a relative stability to each planform type.

Multi-channel patterns may be braided or anastomosed. Anastomosed channels are multiple channels separated by stable bars and islands. They are sometimes considered a subset of anabranched channels, where a branch of the river diverges and then reenters the main stem downstream. Braided channels also have multiple flow paths. Mid-channel bars separate the flow at lower discharges but are submerged at high discharges, so there is a single channel at the surface. Braided channels are characterized by high sediment load and high stream power and they usually have erodible banks. The degree of braiding can be quantified using a variety of indices, which are generally of two types. One type calculates the total length of all the individual channels that extend the whole length of a given reach, divided by the mid-channel length of the main-stream channel length in the reach. The second type counts the number of active channels or braid bars per channel transect. Bridge (1993) states that the second type is preferable because it is not a function of individual channel sinuosity.

The degree of channel meandering can be characterized by sinuosity. Sinuosity for a given river reach is defined as channel length (or channel slope) divided by valley length (or valley slope). The straighter the river channel alignment, the lower the sinuosity and the steeper the slope. If the sinuosity is greater than 1.3, the channel is considered meandering (Federal Interagency Stream Restoration Working Group, 1998).

7.3.2.7 Geomorphic Mapping

The objective of geomorphic mapping is to identify and locate geomorphically significant features on the study site landscape that impact river processes. These features may include bedrock outcrops, landslides, debris fans, alluvial fans, bars, tributaries, distributaries, flood plain and terrace boundaries, and side channels. Typically, the map distinguishes categories or units of similar characteristics. These characteristics include age, origin or process, landform and material or structure. It is assumed that areas of the same unit type will behave in a similar manner. The map becomes an effective source of data that enhances understanding of the landscape and prediction of responses to changes in the system. It is useful in restoration projects to help identify factors that may control the system and to evaluate potentially self-sustaining modifications to the system.

Watershed topographic parameters such as slope angle, aspect, and relief; vegetation type; rock type, age, and structure; soils; land use; and surface drainage are commonly used in classifying watersheds. Dominant processes such as fluvial, eolian, weathering, glacial, ground water, tectonic, coastal, and anthropogenic activities may also be used to differentiate among watershed types. Vegetation can provide clues to the underlying material. For example, changes in species or successional stage often are a result of differing soil or geology. Fluvial features such as tributaries, terraces, flood plains, current and past channel patterns, sediment type and size, bed control, channel geometry, and slope can be used to classify units associated with the channel.

Soil profiles can be used to describe the soil stratigraphy and to assess the ages and continuity of successive deposits, including terraces. Stratigraphic data can be helpful in assessing bank erodibility. Soil profiles can be described from the examination of river and terrace banks, escarpments, pits, and drill logs. A particularly useful source of soil data is soil surveys. Soil surveys are commonly produced in the United States for agricultural areas. Soil types and ages can help identify landforms that have undergone similar processes. Soil types can be identified by sediment source, erodibility, land use, vegetation, mapping for wetland, upland, and chemical composition. Frequently, archaeological assessments use the stratigraphic context to locate potential sites. Sedimentation and erosion rates can often be estimated from radiocarbon dating of terraces or other fluvial features. Other useful data are geologic events, processes which may identify post-depositional modification, and climatic trends (Birkeland, 1999).

The level of detail and scale of the map is dependent on the intended use of the final product (Compton, 1962; Bureau of Reclamation, 1998). Drainage basin and valley parameters may be adequately represented at a scale of 1:24,000, but for channel features 1:10,000 or smaller is an appropriate scale. Detailed mapping of specific sites may require finer scales to portray features of interest. Project goals and objectives will help determine the appropriate scale.

Information sources for geomorphic mapping include historic maps; aerial and ground photographs; bathymetric, ground, and aerial surveys of the river channel, flood plains and terraces; land use records; and field inspections. Government agencies such as Natural Resources Conservation Service, Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. Forest Service, state land-use agencies, local conservation districts, and local planning and zoning agencies are excellent resources. U.S. Geological Survey (USGS) has both topographic and geologic maps available, typically at large scales. Field surveys will provide more precise topography data than typical USGS maps, especially for areas along the active river channel and flood plains. Field verification of mapping results should be accomplished for all remote sensing data. The reliability of historical data must be assessed and cross-correlated to determine the significance of the information.

A Geographic Information System (GIS) is a tool for storing and analyzing spatial data sets. The Federal Geographic Data Committee defines GIS as "A computer system for the input, editing, storage, retrieval, analysis, synthesis, and output of location-based information. GIS may refer to hardware and software, or include data" (Office of Management and Budget, 2002). Maps, aerial photos, land use records, etc., can be digitized into separate "layers," describing a single type of information. Separate layers might include topography, geology, soils, geomorphology, and land use. The layers are geo-referenced and can be displayed together at the same scale. Relationships between disparate information sources can often be identified with this tool; for example, how certain channel features are dependent on geologic features. Several useful parameters including sinuosity, channel width, and planform classification can be measured using GIS mapping tools.

If the study reach is not in equilibrium, a reference reach with similar fluvial, geomorphic, and sedimentary processes may provide stable channel form information. Ideally, the reference reach is in an undisturbed condition and within the same watershed. Classification systems (see Section 7.3.2.9) are useful to identify reaches that are similar. Care must be taken in scaling measurements from reference reaches. Osterkamp et al. (1983) and Dodds and Rothman (2000) provide discussions of scaling relations.

7.3.2.8 Channel Geometry Analysis

Many methods have been proposed over the years to predict stable channel geometry. Most calculate width and depth and use discharge as the independent variable. Many equations neglect sediment entirely, others use the bed-material sediment size, and most assume a constant sediment-discharge relationship.

The hydraulic geometry approach (Leopold and Maddock, 1953), uses power equations to define relationships among channel variables based on bankfull discharge. Williams (1978) presents values of the coefficients of those power equations for 165 channels. The regression coefficients do vary between locations and flow regimes and must be checked for applicability to a specific site.

Several regime equations describing channel geometry have been developed based on measured data of many rivers. Lacey (1929), Simons and Albertson (1963), and Blench (1957) are commonly used for sand bed streams. Gravel bed equations include Kellerhals (1967), Bray (1982), and Hey and Thorne (1986). Julien and Wargadalam (1995) use a semi-theoretical approach based on the principals of open channel flow. Again, these equations are applicable only to the specific river conditions that the equations were based on and must be selected carefully.

Soar and Thorne (2001) present regime equations for both natural sand and gravel-bed rivers considered to be in dynamic equilibrium. Different equations are presented for riverbanks that are resistant to erosion because of riparian trees and for riverbanks that are more erosive because of a lack of riparian trees. For 58 sand bed rivers in the United States, these regime equations explained 85 of the variance in bankfull width as a function of bankfull discharge (see Table 7.1).

Other approaches use minimum stream power, sediment concentration, or energy dissipation to predict channel shape. Yang (1986, 1996), Chang (1988), and Bettes and White (1987) have used minimum stream power to provide a third relationship beyond sediment transport and alluvial resistance relationships to calculate channel geometry. Care must be taken to validate an approach for a particular location and time period.

7.3.2.9 Stream Classification

River channels can be classified based on such parameters as planform, slope, width-to-depth ratio, and bed material grain size. It is assumed that channels in the same class will act in a similar manner. Stream classification systems such as those by Montgomery and Buffington (1998) or Rosgen (1996) can help to define the stable channel dimensions and appropriate management actions. These systems have been used most frequently in gravel and cobble bed channels. A concise discussion of the two systems can be found in Bunte and Abt (2001). Rosgen in particular emphasizes the need for training in the stream classification method for appropriate application.

Table 7.1. Regime equations by Soar and Thorne (2001), which include the 95-percent confidence limits on the mean response

River type	Regime equations in metric units[1]	Regime equations in english units[2]	Number of rivers	Coefficient of determination (R^2)
Sandbed rivers in the United States with less than 50 percent tree-lined banks[3]	$W_b = 5.32\ Q_b^{0.5}\ e^{\pm 0.082}$	$W_b = 2.94\ Q_b^{0.5}\ e^{\pm 0.082}$	32	0.87
Sandbed rivers in the United States with more than 50 percent tree-lined banks. [3]	$W_b = 3.38\ Q_b^{0.5}\ e^{\pm 0.085}$	$W_b = 1.87\ Q_b^{0.5}\ e^{\pm 0.085}$	26	0.85
Gravelbed rivers in the United States with thin bank vegetation[3]	$W_b = 4.17\ Q_b^{0.5}\ e^{\pm 0.087}$	$W_b = 2.30\ Q_b^{0.5}\ e^{\pm 0.087}$	9	0.95
Gravelbed rivers in the United States with thick bank vegetation[3]	$W_b = 3.67\ Q_b^{0.5}\ e^{\pm 0.065}$	$W_b = 2.03\ Q_b^{0.5}\ e^{\pm 0.065}$	14	0.96
Gravelbed rivers in the United Kingdom with less than 5 percent tree and shrub vegetation along the banks[3]	$W_b = 3.75\ Q_b^{0.5}\ e^{\pm 0.064}$	$W_b = 2.07\ Q_b^{0.5}\ e^{\pm 0.064}$	29	0.92
Gravelbed rivers in the United Kingdom with at least 5 percent tree and shrub vegetation along the banks[3]	$W_b = 2.48\ Q_b^{0.5}\ e^{\pm 0.051}$	$W_b = 1.37\ Q_b^{0.5}\ e^{\pm 0.051}$	33	0.93

[1] The bankfull discharge (Q_b) is in m^3/s and the bankfull width (W_b) is in meters.

[2] The bankfull discharge (Q_b) is in ft^3/s and the bankfull width (W_b) is in feet.

Note: The term, $e^{\pm 0.0xx}$ in these equations, accounts for the 95-percent confidence limits on the mean response.

7.3.2.10 Channel Adjustments and Equilibrium

An alluvial river channel is continually adjusting to achieve dynamic equilibrium between discharge, sediment supply, channel geometry, and slope. A disturbance to the river system, such as the construction of a storage dam, occurrence of landslides, or removal of riparian vegetation can disrupt this equilibrium. For example, when a reservoir traps sediment, water released from the reservoir will commonly scour the riverbed below the dam, causing channel degradation. Degradation continues until a new dynamic equilibrium is established. Dynamic equilibrium for a river channel can be defined as the condition where, over the long term, the river's sediment transport capacity is in balance with the upstream sediment supply. The river will continue to adjust its bed and banks in response to changing hydrologic and sediment supply conditions. Lane (1955) developed a qualitative relationship between sediment load and size, and river slope and water discharge:

$$Q_s d \propto Q_w S \tag{7.1}$$

where Q_s = sediment load (of sizes represented in the riverbed),
d = sediment particle diameter of the riverbed,
Q_w = water discharge, and
S = river channel slope.

In Lane's relationship, when the sediment load is reduced, the average sediment particle diameter of the riverbed will tend to increase and the channel slope will tend to decrease. If water discharge is decreased, the river slope will tend to increase and the sediment particle diameter will tend to decrease.

Yang (1986, 1996) theoretically derived a quantitative equation for the prediction of dynamic adjustment of a river channel based on his unit stream power equations (1973, 1979).

$$\frac{Q_s d^{J/2}}{K} = \frac{Q_w^{J+1} S^J}{A^J} \tag{7.2}$$

where K = site-specific coefficient,
J = site-specific exponent,
A = channel area ($A = WD$),
W = channel width, and
D = hydraulic depth.

For most natural river channels, the exponent J has a value between 0.8 and 1.5. If an average J value of 1 is used, the above equation can be simplified to

$$\frac{Q_s d^{0.5}}{K} = \frac{Q_w^2 S}{WD} \tag{7.3}$$

Yang's equation is similar to Lane's relationship, but Yang's equation can be used directly to predict the dynamic adjustments of a river channel due to natural or anthropomorphic events, after the coefficient K has been determined for the river. Water discharge is raised to the second power, demonstrating that channel adjustments are most sensitive to changes in water discharge.

River channels can experience change in planform, slope, cross section, and bed topography. Planform changes can be a shift in classification (i.e., straight to meandering), where the rate of change might be the distance per time progression of the shift upstream or downstream. Within a classification, variables that can be measured include channel location, meander wavelength, bend radius of curvature, channel width, sinuosity, shape and size of main bars or islands, braiding intensity, and degree and character of anabranching.

Slope changes over time should compare elevation of the same feature type (i.e., thalweg to thalweg not thalweg to average bed) at the same location. Bed control locations may be identifiable in this analysis. Reach averages of slope may be used when channel locations change. Channel shape changes over time are evaluated through the cross section geometry and bed topography. A plot with serial cross section surveys is a very effective method to visualize change. Parameters such as width, depth, flow area, and bank erosion are easily calculated from the survey data. Bed topography is frequently assessed by reach (e.g., island acreage or number and spacing of pool and riffle sequences).

The amount and rate of change can be derived from comparison over time of the parameters discussed above, assuming enough data are available. Comparison of channel characteristics (such as channel capacity, stage-discharge rating curves, and bed material grain size) with a known stable reach (reference reach) can be very insightful. Reach averages may be used for comparison of all variables discussed above. Other data from a chronology of events and disturbances can be used in the analysis of channel change. The chronology may contain information from maps, historic construction documents, climate and hydrology data, and anecdotal evidence. The established sequence of events may provide needed information to correlate or explain the changes shown in historical data analysis.

Rates of change as affected by process are used to predict channel responses to disturbances. Trends of channel evolution can be unsteady, nonuniform, and complex (Simon and Thorne, 1996), so it may not be appropriate to predict only by historical trends. Another concern is a possible change in measurement techniques and equipment over time because the characteristic being compared may not be the same.

River channel stability may be assessed through the following indicators:

- Amounts and rates of historical changes of bed elevation and horizontal position,
- Sediment transport capacity,
- Channel bank stability,
- Planform characteristics such as sinuosity or meander wavelength,
- Comparison of channel planform with a known stable reference reach,
- Channel hydraulic capacity (bankfull discharge),
- Stage-discharge rating curves, and
- Bed-material grain size distributions to cite several examples.

More than one approach may be used to check various processes in the stability assessment.

7.3.2.11 Geomorphic Summary

Geomorphology can help identify critical reaches and how the project fits into the context of the entire system. Several steps are involved in the geomorphic analysis, including defining channel form and processes, mapping, assessing river channel stability, and identifying disturbances affecting the river corridor. Understanding how and why a system changed will assist in assessing the stability of the proposed restoration. Two publications with useful information on performing a geomorphic analysis are *Stream Reconnaissance Handbook* by Thorne (1998) and *Hydraulic Design of Stream Restoration Projects* by Copeland et al. (2001).

7.3.3 Disturbances Affecting the River Corridor

To have a successful river restoration project, it is essential to understand what types of disturbances have played a role in forming the current channel configuration, which disturbances are presently continuing, and which are likely to occur again in the future. For this section, a disturbance is defined as a detectable change to the natural sedimentation processes of erosion, transport, and deposition that alters the physical characteristics of the stream channel, flood plain, and riparian zone. A natural fluvial process such as landslides, fire, floods or human-induced impacts such as levees, bridges, and dams may cause the disturbance to occur. In general, natural disturbances may be less frequent than human disturbances, which often affect the river on a continual basis. The magnitude and duration of the disturbance directly depend on the location and characteristics of the process that triggers the change. For instance, if a landslide in the upstream watershed occurs during a storm event, a large pulse of sediment would be delivered to the river channel and turbidity would likely increase. However, the delivery of suspended sediment to the river would be limited to the duration of the storm event. On the other hand, a permanent levee along the river corridor may constrict the channel width and have long-term impacts on river channel bed-material size and sediment transport capacity. It is important to identify not only the existing disturbances in the river and watershed, but also the historical disturbances. Recognizing the historical disturbances can help identify natural disturbances in the watershed that are likely to occur again and human disturbances that have played a role in forming the current river channel configuration.

Natural disturbances such as floods, droughts, wind storms, fire, landslides, debris dam failures, volcanic eruptions, and earthquakes can all result in a change in sediment processes in a river system. Many natural disturbances like volcanic eruptions and earthquakes occur on an infrequent basis. These types of disturbances are hard to predict, but they can play an important role in understanding how the existing river corridor came to its present state. Other natural disturbances such as fires, floods, and landslides occur on a more frequent basis and are easier to predict the potential for repeat occurrence in the future.

A great source for locating available documentation, research, and analysis on natural disturbances is local, state, and federal government agencies. It is important to look for information not only at the site of interest, but also in areas further upstream that may contain disturbances that affect the area being considered for restoration. Another option for documenting historical disturbances is to use historical aerial photographs and maps. In many areas, digital ortho-rectified photographs are available that can be used to create a data base of existing and historical aerial photographs and maps in a geographic information system. With this modern technology, impacts from floods, occurrence of landslides, and other natural disturbances can be quickly analyzed. Another source of valuable information is interviews with local landowners. Although mostly undocumented information, landowners often experience natural disturbances to the river corridor firsthand and can be an excellent source for better understanding the impact and timing of historical events not otherwise documented.

Activities that can cause disturbance to the river corridor include the construction of dams, diversions, levees, roads, and bridges; bank protection;, removal of large woody debris; logging;

grazing;, gravel mining; urbanization;, and recreation. The most common form of human-induced disturbance of sediment processes is the construction of features that alter the hydraulics and geomorphic characteristics of the river channel and flood plain (e.g. channel width, depth, slope, roughness, and alignment). These features may cut off flood plain area, alter channel planform, reduce incoming sediment, induce channel and bank erosion, or change the capacity to transport and store sediment. The following topics briefly discuss some of the more typical human-induced disturbances and how they impact sediment processes on rivers. A more detailed discussion on these topics can be found in the *Stream Corridor Restoration Manual: Principles, Processes, and Practices* (1998).

7.3.3.1 Dams

According to the *National Inventory of Dams* (U.S. Army Corps of Engineers, 1999), there are currently over 76,000 dams in the United States. Many of these dams are built across rivers and alter sediment transport delivery rates and volumes. Dams create impoundments (reservoir pools) and, if these impoundments are large enough, they can trap sediment delivered from the upstream watershed and result in clear water releases downstream.

Large dams create significant impoundments that may take centuries to completely fill with sediment. If the clear water releases are sustained for long periods of time, net erosion can result as the existing sediments along the bed are gradually transported downstream. A reduction in the sediment supply to the downstream river channel can alter the sediment sizes present along the channel bed. While smaller dams can locally impact the sediment regime near the dam, they have limited impact on reducing sediment delivery downstream. They may initially trap sediment in the impoundment, but once the available storage is filled, sediments can once again be transported over the top of the dam during high flows.

In addition to reducing sediment delivery to the downstream river, dams can also alter natural flow regimes. The majority of sediment transport occurs at high flows when a significant portion of the channel is inundated. If dam operations reduce the frequency or magnitude of peak flows, this will reduce the sediment transport capacity of the downstream river. When significant sources of sediment are available in the downstream channel from downstream tributaries or bank erosion, this reduction in peak flows and sediment transport capacity can result in aggradation. All of these possibilities should be taken into consideration when assessing a river with upstream dams. The USGS has published two studies on the impacts of dams, which are *Downstream Effects of Dams on Alluvial Rivers* by Williams and Wolman (1984) and *Dams and Rivers Primer on the Downstream Effects of Dams* by Collier et al (1996). These two publications describe many of the different types of impacts on the downstream river channel that can occur as a result of dams.

Because there are natural processes that reduce the useful storage in a reservoir, these losses, over time, decrease the reservoir sediment trap efficiency and increase the portion of sediment released to the downstream river channel. Reservoir storage losses due to sedimentation may reduce the reservoir's detention of floodflows and change the frequency distribution of controlled and uncontrolled flood outflows. Thus, the hydrology of a river downstream from a reservoir changes, usually slowly, throughout the life of the reservoir. Some reservoirs have very small sediment inflow rates and very long lives. Those with little or no sediment inflow are usually off channel storage reservoirs.

The operating rules that govern the various outflows of water from the reservoir and its canals determine the hour-by-hour and day-by-day controlled flows that enter the downstream river. The controlled flows may range from a minimum of no outflow at all to large spillway outflows controlled by gates on the spillway crest. The controlled flows are frequently limited to a range, or ranges, of flows by the structures that release the water from the reservoir. The operating rules may release water in more limited ranges, and those ranges may depend on the season of the year, the water level in the reservoir, and downstream water needs.

Dams may also trap contaminated sediments that originate from historical mining sites or other unregulated nonpoint pollution sources upstream. When considering releases of sediments from reservoirs through either dam removal or low-level release operations, the potential for releasing contaminants should be assessed. An additional discussion related to impacts from decommissioning dams is discussed in Chapter 8.

7.3.3.2 Diversions

Water diversion structures remove water from a river to meet the needs of agricultural, industrial, or municipal water users. If a significant percentage of the total volume of flow is removed from the river, hydraulic and sediment processes will be affected. Removal of a significant portion of the total flow can reduce wetted width, depth, and velocities, which can, in turn, increase water temperatures and reduce the area inundated along the channel. If the reduction in flow occurs over a long enough period of time, these impacts will alter the aquatic habitat and, possibly, riparian vegetation along the river channel. As the natural streamflow decreases (especially during low-flow summer months), the amount of flow diversion becomes more noticeable. For instance, during a flood, the flow diversion would likely be a small proportion of the total flow. However, during a river's low-flow period, the flow diversion may be a large portion of the total flow. For this reason, flow diversions may have a significant impact on the aquatic habitat. If flow diversions significantly reduce the mean annual riverflow, then likely they would also significantly reduce the sediment transport capacity of the river channel, which could lead to aggradation of the riverbed.

Unlike storage reservoirs, which often release clear water with no sediment, diversion structures divert water but try not to divert sediment. Because the water volume is reduced, the transport capacity is reduced and additional deposition in the downstream channel may result. If this happens, increased deposition can result in higher levels of flooding and increased lateral channel migration and bank erosion. Restoration strategies on rivers with diversions should consider the timing, magnitude, and duration of flow diverted, as well as how this may impact the flow regime and the annual sediment transport capacity. In many areas where flow reduction from diversions has significantly altered habitat, restoration work has focused on defining a minimum riverflow in order to provide a particular amount of habitat area. Periodic high flows may be needed to increase the annual sediment transport capacity of the downstream river channel.

7.3.3.3 Levees

Levees are an artificial embankment (usually earth and rock) built along a river to protect an area from flooding or to confine water to a particular channel path. Levees built in the active channel or flood plains have a greater impact on river hydraulics and sediment transport than levees built along a terrace and outside of the historic channel migration zone. The larger the portion of channel and flood plain that a levee cuts off, the greater impact it will have on hydraulics, sediment transport, and geomorphic processes.

Flood plain sediments are naturally deposited and reworked by the river as the channel migrates across the flood plain. Flood plains also tend to temporarily store floodwaters and attenuate and slow flood peaks that pass to downstream reaches. When the flood plains are cutoff by levees, channel migration is restricted and flood peaks will pass more quickly to downstream river reaches and with less attenuation. As levees force more water to flow in the main channel, they result in higher river stage, depth, velocity, and sediment transport capacity. If levees force the river to flow in a straighter alignment, then slope is also increased, which further increases flow velocity and sediment transport capacity. These increases often result in channel incision or degradation, coarser bed material, and even armoring of the riverbed. The increased depth and velocity also increase the capacity to transport large woody debris, which reduces the number of logjams present in the constricted reach.

In some cases, levees are not built a consistent distance away from the river channel and can locally create channel constrictions. Where the levees form a constriction, they result in a local increase in the velocity and sediment transport capacity at the constriction, and cause backwater upstream. Upstream from the constriction, sediment can deposit in the backwater areas and aggrade the channel bed. In this manner, the levee constriction can act in a similar way to a bridge constriction. This fluctuation in distance from the levee to the riverbank can result in a variation in sediment transport capacity with alternating reaches of erosion (in constricted areas) and deposition (in backwater areas upstream of constriction). For example, levee constrictions along the Dungeness River near Sequim, Washington, resulted in 10 feet of local sediment deposition upstream from the constriction points (Bountry et al., 2002).

In the natural setting, a portion of the suspended sediment load (sand, silt, and clay) will deposit on flood plain surfaces during high flows as water overtops the riverbanks. When levees cut off the flood plain, all of the water and suspended sediment remain in the river channel contained between the levees. This can increase the turbidity of the river and reduce the ground water-river interaction processes. In addition to cutting off flood plains, levees can also cut off secondary channels that are important for fish and other aquatic animals and plants.

Restoration strategies typically involve the removal or setting back of the levees to allow flood flows to have full or partial access to the flood plain. Properties or easements within the affected flood plain may have to be purchased from private landowners. The degree to which a levee is set back depends on the management objectives and cost. The examination of historical photographs and maps will help determine the boundaries of the natural flood plain and the historic channel migration zone.

7.3.3.4 Roads in the River Corridor

Roads are designed and constructed to provide a safe access route for commercial and private transportation. However, the protection of roads within the river corridor may have an impact on river processes. The degree to which a road may impact a river depends on the elevation of the road relative to the natural topography and the alignment of the road relative to the river channel and flood plain.

The elevation of a road embankment crossing through a flood plain is typically higher than the natural flood plain topography. Therefore, the road embankment can act as a levee and cut off a portion of the flood plain during high flows and limit future channel migration. This can cause water to pond up behind the road embankment as it drains off the terraces or valley walls. If a significant portion of the flood plain is cut off, more water is forced to remain in the river channel, causing increased stage and velocity. However, if the road is positioned at the edge of the flood plain, so the percentage of flood plain area cut off is small, the impact is greatly minimized.

Roads constructed not only in the flood plain, but also parallel to the river channel, can create "hard points" where the road embankment comes into contact with the river. If the natural riverbank is made of a material resistant to erosion, such as bedrock, the impact on river processes is minimal because bank erosion and channel migration are already limited. When the natural bank is made of more erodible materials, such as alluvium or glacial deposits, the river can erode this bank over time as the channel migrates across the flood plain. When the river begins to erode the road embankment, rock riprap is typically used to stabilize the bank and prevent any further erosion from taking place. If designed properly, rock riprap can be an effective embankment protection strategy, but it can result in increased velocities and a deep thalweg adjacent to the embankment toe. The protected bank limits the amount of natural channel migration that can occur. If riprap prevented the natural growth of vegetation along a riverbank, there would be a lack of cover (shade) and recruitment of woody debris. Other options are to construct engineered logjams along the bank to deflect high-velocity flow away from the bank and create downstream eddies that promote sand and gravel bar deposition. Planting trees along the bank can also increase stability although some rock may still be required to protect the toe of the bank from erosion. The installation of bend-way weirs can also be used to deflect high-velocity flows from the riverbank.

Restoration strategies involving roads should consider what the natural bank or topography would be like if the road were not in place, how the road impacts river channel and flood plain processes, what options exist for protecting the road embankment from river erosion, and what options exist for relocating or setting back the road.

7.3.3.5 Bridges

The construction of bridges along a river channel can have a varying level of impact on river channel hydraulics and sediment processes. The extent of the impact is typically limited to several channel widths upstream and downstream of the bridge. The steeper the river, the less distance (both upstream and downstream) from the bridge the effect will extend. Even though a bridge may not constrict the active channel width, a constriction of the channel migration zone, due to an embankment across the flood plain, would prevent future channel migration. For example, when a meander bend migrates downstream and encounters the bridge approach embankment, the river is forced into a sharp bend and then must flow parallel to the embankment before flowing under the bridge. The combination of the sharp river bend and the continuing lateral channel migration often leads to extensive bank erosion immediately upstream from the bridge embankment.

When bridge piers and embankments constrict the active channel and flood plain, they alter the local capacity to transport water and sediment. The constriction causes higher velocities through the bridge, which increase transport capacity. However, a low-velocity backwater area forms upstream of the constriction, which reduces transport capacity and results in deposition of sediment and woody debris, if present in the system. Bridge spans can be lengthened to reduce or eliminate the impact on natural river processes. The amount that a bridge span is lengthened depends on the resource management objectives and costs. However, in many cases, bridges are built on natural geologic constrictions and do not create unnatural constrictions on the river. Restoration strategies at bridge locations should consider whether the bridge is formed at a natural constriction, and what level of impact, if any, the bridge exerts on the river hydraulics and sediment transport capacity.

7.3.3.6 Bank Protection

Bank protection is placed along a riverbank to prevent potential erosion of the bank during floods. However, bank protection typically does not raise the bank elevation like a levee and, therefore, does not prevent floodflows from overtopping the bank. However, bank protection does act to prevent lateral channel migration and erosion. Further, bank protection may cut off access to side channels if their entrance becomes blocked by the bank protection. An important factor in understanding the degree of impact from bank protection on natural river processes is to determine whether the bank is at the edge of a terrace or within the natural flood plain and channel migration zone. When bank protection is placed along a valley wall or along a terrace bank at the edge of the natural flood plain, the impact on channel processes is often negligible. This is because the natural rate of bank erosion and lateral migration along the valley wall is limited, due to geologic controls. When a terrace can be dated as being hundreds or thousands of years old, protecting the edge of the terrace and the historic channel migration zone, is often mitigation for some other impact, rather than a direct effect on natural river processes. However, when bank protection is placed along a younger surface within the flood plain, the impact on bank erosion and lateral migration processes may be significant. The degree of impact depends on the length of bank protection placed on the channel, the amount of active channel or flood plain that is cut off, and the combined effect from any bank protection structures on the opposite bank.

7.3.3.7 Removal of Vegetation and Woody Debris

In a natural setting, trees typically grow along alluvial riverbanks and provide a mechanism for protecting the banks and limiting the amount and rate of bank erosion during floods when high velocity riverflows are adjacent to the bank. Although bank erosion does occur in natural settings, the rate and extent of the erosion is usually limited by vegetation. The root structure of the vegetation increases the bank roughness and provides more resistance to erosion. As small amounts of the bank erode, large trees can fall into the river channel and line the bank, which tends to naturally protect the bank by deflecting high-velocity flows away from the bank.

Development along rivers often involves removal of riparian forests from the riverbanks and flood plain. When vegetation is removed, this important natural bank protection feature is lost. Subsequent flooding in the river can result in large amounts of bank erosion where vegetation has been cleared, especially along the outside curve of meander bends. Historical aerial photographs can be used to document when vegetation was cleared in a particular area, and the resulting bank erosion that has occurred from subsequent floods. Field investigations of the materials that comprise the bank are also important to assess the potential for bank erosion in areas where vegetation has been cleared.

In many river systems, woody debris was historically removed from the river channel to improve conveyance of water or for navigation purposes. The presence of large woody debris in the river channel tends to increases channel roughness. If large woody debris were removed from the river channel, the river would be left with excess energy. One possible response would be an increase in sinuosity and a corresponding reduction in river slope to reduce the excess energy. Such an increase in sinuosity could lead to an increase in bank erosion and, possibly, an expansion of the historic channel migration zone.

7.3.3.8 Forestry Practices

Forest harvest, road building, road maintenance, and other management activities in the upstream watershed can result in a net increase in water and sediment delivery to the mainstem river channel and tributaries within the watershed. Another potential impact from forestry activities is a loss of slope stability resulting in landslides or debris flows.

Increases in the coarse sediment supply from tributaries and the upstream river channel have the greatest potential to affect the physical characteristics of the channel planform and geometry, while increases in the suspended sediment load can result in increased turbidity, poor water quality, and degraded aquatic habitat. Many investigators have suggested that increases in coarse sediment from the watershed can be detected by increases in channel width, but that increases in peak flows from forestry practices can have the same result (MacDonald, 1991). Channel changes can often have multiple causes and can include both natural and human factors. Therefore, the impact from forestry practices must be carefully assessed through quantitative measures, where possible, and qualitative measures at a minimum. Useful information for this assessment includes the proximity of the forestry practice to the affected site, the relative percentage of land affected in the upstream watershed, the impact on the stream channel and landscape as a result of the forestry practice, and the existing land use following forest harvest.

7.3.3.9 Grazing (bank erosion)

Grazing or trampling of the vegetation along a river corridor can accelerate bank erosion. Grazing practices that allow free animal access to the river may also result in bank erosion from the physical trampling of the banks by animals accessing the river.

7.3.3.10 Gravel Mining

Gravel mining is the physical removal of sediment from a river channel and is often accomplished by scraping gravel bars or excavating material from areas adjacent to the active river channel with mechanical equipment. The impact of gravel mining can be determined by assessing the rate, duration, and volume of sediment removed relative to the incoming sediment load of the river. In addition, gravel mining in the active river channel results in a lowering of the channel bottom, which will have local impacts on hydraulics and sediment transport processes. For example, gravel would tend to deposit and refill the excavated areas. If a gravel pit in the channel is long enough, the hydraulic slope entering the gravel pit will become steep and headcut erosion of the river channel will tend to migrate upstream.

Records of gravel mining quantities and frequency are often difficult to find for historic operations, but, more recently, local governments have required permits to mine gravel and information is more readily available. The volume of gravel mined from the river can be evaluated to determine the impact on the sediment budget for a particular river reach.

Historically, mining occurred in and adjacent to a large number of rivers, and piles of sediment were often overturned and left behind in search of minerals and precious metals. The physical movement of river and flood plain materials can have a significant impact on hydraulics and sediment transport. In addition, sediments left behind in mining waste piles may contain contaminants that must be addressed, if present. Otherwise, these contaminants can enter the streamflow and affect water quality as sediments are mobilized during high flows.

Gravel mining or bar scalping has been used as a management tool to help control aggradation. Long-term aggradation should be documented through repeat cross-section measurements and, if present, the cause of the aggradation should be determined before employing gravel mining as a management strategy.

7.3.3.11 Urbanization

When areas along a river corridor are urbanized, the surfaces are often cleared of vegetation and significant flood plain areas become paved with asphalt or concrete. Creating impervious surfaces can increase the volume of water conveyed to the river channel during storm events and flooding. In a natural setting, water overtops riverbanks during flooding and can be temporarily stored along the river's flood plain. A large portion of the water that enters the flood plain will pond up and gradually seep through the soil into the ground water thus limiting the amount of floodwater that re-enters the channel during the peak of the flood. When flood plain surfaces become impervious, water will quickly run off that surface and flow back into the river channel, which can increase the volume of water delivered to the river. Determining the amount of area urbanized and proximity to the river channel can help assess the degree of impact of impervious surfaces. In addition, if contaminants from nonpoint surface runoff are present, they also need to be addressed in restoration plans.

7.3.3.12 Recreation

Most recreational river users are very respectful of the environment and work to preserve natural river conditions. However, certain activities by recreational river users can begin to impact natural river processes if sustained over long periods of time. One example might be wakes created by jet boats along a riverbank that lead to accelerated bank erosion. Another example is the compaction of soils and erosion from human and vehicle use on river access roads, trails, and camping sites. Restoration plans should take into account the amount of existing and planned future recreational use and access at a given site.

7.3.4 Hydrologic Analysis

A hydrologic analysis provides information that describes the magnitude, duration, and frequency of discharge on a river. It also provides an understanding of the seasonal variations of flow and the time at which channel forming flows are likely to occur. For example, floods may be short-duration events that occur from winter rains, long-duration events that occur during the spring snowmelt, or rain on snow events, or combinations of all three. Understanding the watershed hydrology is an important step in understanding the sediment processes in the river channel. The hydrologic analysis may also need to investigate the relationship between flow in tributaries and the main river channel, and the interactions with groundwater, to determine if river reaches tend to lose or gain water.

7.3.4.1 Historical Discharge Data

Hydrologic analyses are usually based on continuous discharge records from river gaging stations at one or more locations on a river. In addition to discharge data, gaging stations also often contain water surface elevation measurements, velocity data, and cross-section geometries used for measuring discharge. Discharge information can be downloaded from the USGS web page (www.usgs.gov). Other sources include the River Forecast Centers of the National Oceanographic and Atmospheric Administration, agencies or companies that operate dams, water treatment facilities, ferry boats, drawbridges, etc. When evaluating historical discharge records, it may also be of interest to look for trends in riverflow. River hydrology variations can be over short or long-term periods and can be caused from a number of influences such as climatic fluctuations, land use changes, river diversions, upstream reservoirs, and consumptive use.

When a stream gage does not exist, it may be possible to extrapolate the data from another location in the watershed or a nearby drainage area with similar characteristics. When streamflows have been significantly altered, for example, by storage reservoirs or flow diversions, it may be desirable to determine the natural historical flows without the presence of these impacts. A natural flow reconstruction would then help determine the effect that reservoirs and flow diversions have had on sediment transport processes.

7.3.4.2 Flood Frequency Analysis

Identifying the magnitude and frequency of potential future floods is an essential component of any river restoration project. Flood frequency analysis provides an estimate of the probability of future flood events. Usually, annual instantaneous peak flows are used for this analysis because they indicate the maximum discharge a river may be subjected to. A partial duration analysis uses all flood peaks above a certain base magnitude and is useful when multiple flood events within a single year are important. Flood frequency analyses are used to provide a range of riverflows for hydraulic and sediment transport analyses that may be used to compute the extent of flooding or hydraulic and sediment parameters. They are also used to identify potential design floods for bank protection and river restoration projects. Typical frequencies are the 1.5-year, 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 200-year floods, depending on the extent of historical discharge data available.

7.3.4.3 Flow Duration Analysis

A flow duration analysis is used to show the percentage of time a given flow is equaled or exceeded within a given timeframe. A flow duration analysis is typically based on mean-daily flow data, rather than peak flood values as in the flood frequency analysis. The most commonly referenced values from this analysis are the flows that are exceeded 90, 75, 50, 25, and 10 percent of the time. Flow duration analyses can be performed for all flows within a given number of years. The flow duration analysis can also be performed on data that are segregated by season or month within a given number of years. A comparison of the flow-duration values over different time periods can be used to assess flow changes due to climate change or the influence of water resource development.

7.3.4.4 Ground Water Interaction

Evaluation of the hydrologic interaction between ground water and surface water in a river channel may also be of interest for a restoration project. Migration of the river channel and significant aggradation or incision of the channel bed can cause changes in the ground water and surface water relationship. For instance, side channels through the flood plain may provide viable aquatic habitat when there is a surface water connection with the main channel. However, the side channels can become disconnected from the main channel if the riverflow decreases too much or if the river migrates away from the side channel entrance. In some cases, the groundwater table may be high enough to maintain water in the side channel and maintain the aquatic habitat. The basic linkages between flow in the main river channel and side channels can be determined from simultaneous discharge measurements (including flow depth, width, and velocity) in the main river channel and in side channels. A study of well data and the direction of ground water flow can help identify areas where there may be an upwelling or downwelling of ground water into the side channels or main river channel. Such areas may provide import habitat for fish.

7.3.4.5 Channel Forming Discharge

The channel forming discharge is an important concept for the evaluation of river channels and is often used for design purposes. River channels continue to evolve with time. The river channel cross section and planform are actually formed by a range of discharge values. Large and infrequent floods have the capacity to temporarily shape and modify the channel, but they occur too infrequently over the long term to sustain the channel shape. Low flows occur frequently, but they have too little stream power to shape the channel. Therefore, a range of high flows that occur frequently enough are responsible for shaping the channel over the long term. The channel forming discharge is an index to this range of channel forming flows. It is also called the dominant or formative discharge and often equated to bankfull discharge, effective discharge, or specified by a flow recurrence interval commonly in the range of a 1- to 2.5-year event (Leopold, 1994). The duration of the channel forming flow and the quantity of sediment transported has a role in determining the channel forming flow that is as great as the role of the recurrence interval of the flow.

Ideally, the channel forming discharge is the flow that just fills the active channel to the top of its banks. The channel forming discharge will equal the average bankfull discharge on a river in a stable or equilibrium condition. The difficulty lies in finding a river in a stable or "undisturbed" condition. If there are recent changes (e.g., the historic flows of the river have changed, the sediment transport has been altered, or there have been physical changes to the geometry of the channel including slope), then the channel is no longer in a stable or equilibrium condition and the bankfull discharge represents a previous condition. Incised channels provide a standard example where a bankfull discharge will not represent the channel forming discharge. Even with a stable system, irregularities in a natural channel can make it difficult to pick out a bankfull discharge. Vegetation found along the channel banks can help define the bankfull discharge. Depending on the environmental conditions, the indicator could be the beginning of significant vegetation growth or the line of significant change in vegetation type. This is surprisingly apparent, even in an urban concrete lined channel, where the crack between sloped concrete panels can produce vegetation above a recurring flow line. In some cases, a range of bankfull values may be more appropriate than selecting a specific value.

The channel forming discharge has also been based on a recurrence interval. Leopold (1994) stated that most investigations have concluded that the bankfull discharge recurrence intervals range from 1.0 to 2.5 years, and the bankfull discharge recurrence interval is often assumed to be 1.5 years. For 58 sand bed rivers in the United States that were determined to be in a stable and natural condition, 83 percent had a bankfull discharge with a recurrence interval of between 1 and 2 years (Soar and Thorne, 2001).

Effective discharge is the discharge that transports the greatest amount of sediment over a period of many years or a few decades and has been used to estimate the channel forming discharge. This approach is based on the assumption that channel forming processes are primarily a function of sediment transport. The discharge and sediment transport history are combined to determine the flow range that transports the most sediment over the long term. Papers by Andrews (1980) and Biedenharn et al. (2000) describe the process for calculating effective discharge using equal discharge increments. Cohn (1995) discusses statistical concerns associated with effective discharge computations. Soar and Thorne (2001) found that the effective discharge, computed using equal discharge increments, underestimated the bankfull discharge at 86 percent of the 81 sand bed rivers they investigated. If much more than 50 percent of the long-term sediment load is transported by discharges greater than the computed effective discharge, the computed value is too low and requires adjustment (Soar and Thorne, 2001). The effective discharge can also be computed using probability intervals, which may be more representative of the bankfull discharge. In addition, the median sediment transporting discharge can be computed where half of the long-term sediment load is transported by discharges that are greater and the other half by discharges that are lower (see Chapter 9).

7.3.5 Hydraulic Analysis and Modeling

Restoration strategies often involve modifications to the existing river channel geometry and flood plain, either directly through construction at a particular site or indirectly by altering the flow and sediment regime of the river. A hydraulic analysis gives information regarding the slope, hydraulic geometry, unit stream power, shear stress, and overall energy of the river at a variety of discharges for the existing system, while also providing predictions of how the river will respond to any proposed modifications. A hydraulic analysis can be as simple as performing normal depth calculations of depth and velocity at a given location or as complicated as running a three-dimensional computer model or constructing a physical laboratory model to simulate the river channel hydraulics. When selecting the type of hydraulic analysis for restoration efforts, the key is to choose the level of analysis that will provide the necessary information for restoration planning, alternative selection, design, implementation, and monitoring efforts, while working within the project budget and timeframe.

7.3.5.1 Topographic Data Needed

The basic input data needed for any level of hydraulic analysis are the geometry and longitudinal slope of the river channel and flood plain. These data can be in the form of surveyed cross sections or continuous topography (methods of collecting this data are discussed in Chapter 9). No matter what method is used, a critical criterion for collecting data in natural channels is to ensure that the level of detail in the collected data matches the needs of the specified analysis.

For instance, if it was desired to use a numerical hydraulic model to simulate a flood over several miles of river, the spacing and detail of cross-section geometry could be much greater to represent average conditions than when modeling a short reach during low flows that would be much more sensitive to changes in channel geometry. Another source of data that can be useful is discharge measurement records at gaging stations. Gaging stations are usually located at stable sections. Available data often include monitoring of the channel geometry over time, which can help modelers better understand the range of natural fluctuation (erosion and deposition) along the channel bed as a result of floods, along with velocity measurements, which can be used to calibrate models.

7.3.5.2 Longitudinal Slope and Geometry Data

The first step in a hydraulic analysis is to evaluate the measured longitudinal slope and geometry data along the river. Are there areas of significant change in slope that may indicate a change in hydraulic and sediment transport capacity? Where are the expected areas of highest unit stream power or shear stress in the channel? What depositional features exist in the channel? What are the "wetted width to depth" ratios? Is the channel deep and narrow or wide and shallow? Are there multiple flow paths or a single channel? Do the active channel and flood plain have a consistent width or change as a result of manmade or natural geologic features? Combining these types of questions with the geomorphic analyses will help provide an assessment of the existing system and its capability to move water, sediment, and woody debris.

7.3.5.3 Physical and Numerical Models

To enable prediction of hydraulic parameters at a variety of discharges or to predict changes as a result of modifications to the river, a numerical or physical hydraulic model can be used. There are numerous models available, and research is always ongoing to improve capabilities in this field.

A physical model can also be a great tool for restoration projects involving modifications to existing water management facilities, or in the design of new facilities. Physical models re-create the actual facility at a smaller scale and can be used to look at both hydraulic and sediment impacts at a small, detailed level as design options are varied. Physical models have been used to evaluate the impact of design options on structures that affect fish protection and passage, aquatic habitat restoration, water quality, river sediment flushing, reservoir and river sedimentation related to hydraulic structures, and erosion control.

Numerical models can be used to compute hydraulic parameters that describe existing river conditions at a range of flows and to predict future conditions that may exist as a result of implementing various restoration options. In either case, the results from a numerical model should be checked with the conceptual model to see if they make logical sense. A simple, common approach for numerical hydraulic modeling is to use an "off-the-shelf software" model to evaluate parameters such as depth, velocity, wetted width, flood inundation, unit stream power, shear stress, Froude number, etc. Examples of one-dimensional models include the U.S. Army Corps of Engineers' HEC-RAS (2002); the Bureau of Reclamation's GSTAR-1D (Yang et al, 2004, 2005), GSTARS 2.1 (Yang and Simões 2000), and GSTARS3 (Yang and Simões 2002); and the Danish Hydraulic Institute's Mike 11 (2003). Numerical models can vary in complexity, ranging from steady to unsteady flow, one-dimensional to three-dimensional flow, up to models that integrate groundwater interaction, surface runoff, tributary inflows, diversions, structures, and sediment transport. In other more complex restoration cases, numerical models must be custom developed to properly address restoration project objectives. For instance, the Bureau of Reclamation developed a numerical model for the Platte River in Nebraska (Murphy and Randle, 2003) that integrates hydraulics, sediment transport, deposition, erosion, and the growth and removal of vegetation to address geomorphic changes in the active river channel and flood plain.

7.3.6 Sediment Transport Analysis and Modeling

When the river is in a dynamic equilibrium, the upstream sediment supply can be transported by the flow, and the net change in sediment deposition or scour along the riverbed is insignificant over the long term. When a restoration project is being considered, the natural dynamic equilibrium of the river may have been disturbed by human or natural influences. For example, a river channel might be degrading downstream from a dam or through a reach constricted by levees. The channel might have already reached a new equilibrium for the disturbed condition. Therefore, the existing stability of the river channel and the future stability under the restored condition should be assessed as part of the restoration design. In addition to field inspection and comparison with historic data, the channel stability can be assessed by comparing the upstream sediment supply with the river channel's hydraulic capacity to transport sediment and comparing how this capacity may change along the study reach. Channel degradation would be expected if the sediment transport capacity exceeds the supply, and aggradation would be expected if the supply exceeds the transport capacity.

7.3.6.1 Sources of Upstream Sediment Supply

The first step in understanding the role of sediment in a river is to identify the sources of sediment in the river system. Major sources of sediment often include tributary inflows, landslides and debris flows, hillslope erosion, erosion of banks, and sediment stored along the riverbed and flood plain. Land use changes in the flood plain and upstream watershed can result in changes to the amounts of runoff and sediment supply. For instance, upstream reservoirs, levees, and bank protection may limit additional sediment input to the system by trapping incoming sediment and preventing erosion, but logging roads and development may cause increases in runoff and sediment delivery. In restoration projects, it is important to understand how water management projects and land use changes may be impacting the sediment load of a river, both currently and in the future.

7.3.6.2 Total Stream Power

There are numerous techniques for evaluating the sediment transport capacity of the river (a detailed description of sediment transport capacity is discussed in Chapter 3). When sediment data are limited and the study reach is large, total stream power (γQS) can be a simple technique to show reaches that may have higher or lower sediment transport capacity. Total stream power is based on the product of discharge, the slope of the river, and the unit weight of water (Yang, 1996). In the upper reaches of the watershed, the longitudinal channel slope tends to be steep, but the riverflow tends to be low. In lower reaches of the watershed, the riverflows tend to increase, but the longitudinal slope of the river channel tends to decrease. Thus, total stream power could increase, decrease, or remain about the same with distance along the river system, depending on local geologic and human-built controls. Areas with relatively high total stream power would be expected to have a greater capacity to transport sediment than areas with low total stream power.

7.3.6.3 Incipient Motion

Incipient motion is important for the study of sediment transport, channel degradation, and stable channel design. Incipient motion defines the hydraulic conditions that begin to transport a sediment particle of a particular size along the riverbed. The incipient motion criteria are often used in sediment transport equations and in the design of bank stabilization to determine if the gradation of rock being used is adequate for the design flood. Depending on the application, incipient motion can represent the time at which a single particle begins to move, or the time at which the entire moveable bed is entrained and being transported. Discussions on the methodology for computing incipient motion can be found in Chapter 3 and in several references, such as *Sediment Transport: Theory and Practice* by Yang (1996) and *Computing Degradation and Local Scour, a Technical Guideline* by Pemberton and Lara (1984).

7.3.6.4 Sediment Particle Size Analysis

Sediment data can be collected to define the particle size distribution along the riverbed and the relationship of sediment transport to discharge. Particle size distribution data can provide information on size, shape, specific gravity, and fall velocity of the sediment particles present in the riverbed for a given reach or an entire river system. For instance, it may be of interest to determine if the median size of sediment along the riverbed is decreasing or increasing over a long reach where river slope and bankfull discharge may be changing with distance downstream. Bed-material particle size measurements can also be utilized to help define the geomorphic characteristics of river channel features; such as pools, riffles, and point bars; based on the horizontal and vertical structure of the particle deposits. New techniques are being researched to use bed-material sampling to assess cumulative watershed effects on the river system (Bevenger, et. al, 1995).

Meandering rivers have sinuous planforms and nonuniform bed slopes, with straight riffles connecting curved pools, and have complex spatial patterns of bed-material grain sizes (Leopold and Wolman, 1957; Bunte and Abt, 2001). While the transverse size distributions across riffles tend to be fairly uniform, the transverse size distributions across the curved meander bends tend to have finer bed material on the point bars that are found at the inside bank of each bend and coarser bed material towards the deep, outside part of the bend (Ikeda and Parker, 1989). The size of sediment deposited on a point bar typically decreases in the downstream direction. The sediment particle sizes found in the riffle are typically coarser than those found on the point bar. Particle sizes found in the pool, associated with a meander bend, are typically coarser than the sizes found in the riffle. A frequently found pattern is sand at the point bar, gravel in the riffles, and cobbles in the meander bend pools. In addition, the bed-material grain sizes are associated with the average slope of the river, averaged over many meander bends. The higher the average river slope is, the coarser the bed. Size distributions of bed material will also be affected by the time of sample collection. Finer sediment is often scoured and removed during the rising limb of a flood hydrograph and usually redeposited on the falling limb of the hydrograph, especially in the slower velocity pools. If samples are collected during or after the falling limb of the hydrograph, the bed material samples may not include coarser deposits that may be present underneath the finer sediments, especially in bend pools.

Braided rivers are frequently classified as straight and have uniform bed slopes, but these features depend on the form of the valley along which the riverflows (Leopold and Wolman, 1957; Best and Bristow, 1993). In general, the sinuosity and slope of a braided river follow the pattern of its valley. In any case, the spatial patterns of bed-material grain sizes are not as complex as those of a meandering river. The transverse distributions of bed material tend to be uniform, and the sinuous, riffle-pool sequence is generally absent from the braided river planform and profile. Bed material grain sizes tend to be uniform within reaches with similar channel properties such as slope and width.

An example of grain size distributions across a meandering river channel is given in Figure 7.2, and the variation in median grain size with distance along the channel is shown in Figure 7.3. An example of grain size distributions across a braided river channel is given in Figure 7.4, and the variation in median grain size with distance along the river channel is shown in Figure 7.5.

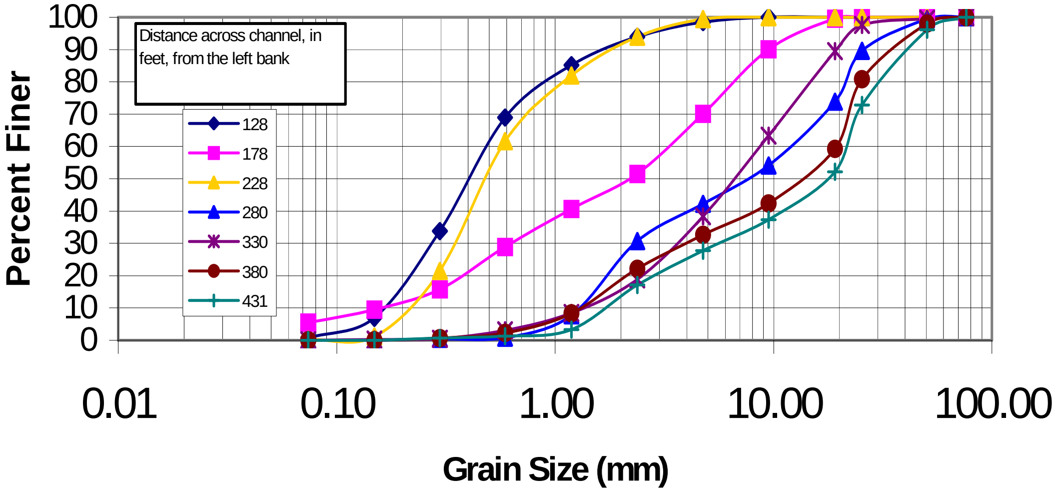

Figure 7.2. Sacramento River, California, grain size distributions across this meandering river channel.

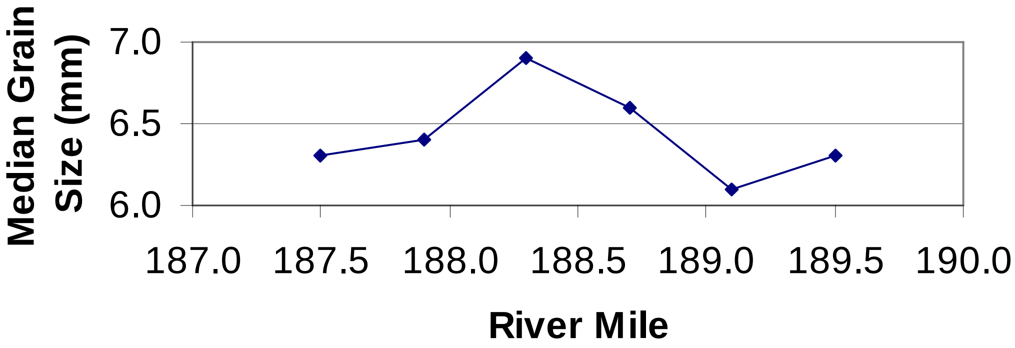

Figure 7.3. Sacramento River, California, median grain size along a longitudinal segment of this meandering river.

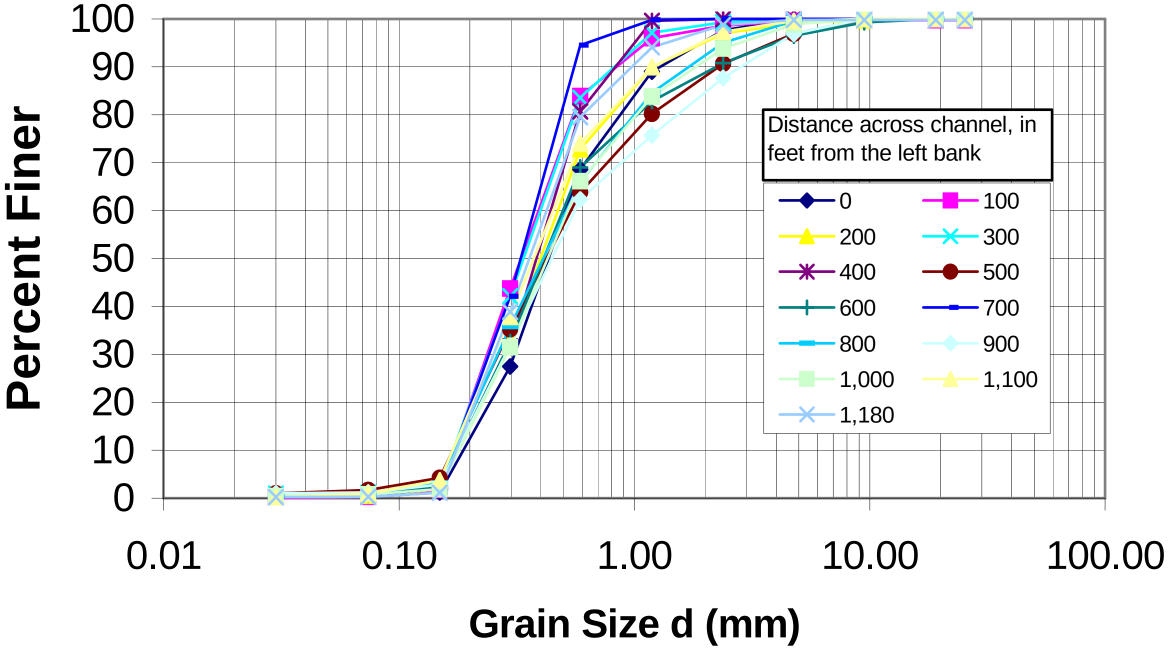

Figure 7.4. Platte River at Kearney, Nebraska, grain size distributions across this braided channel.

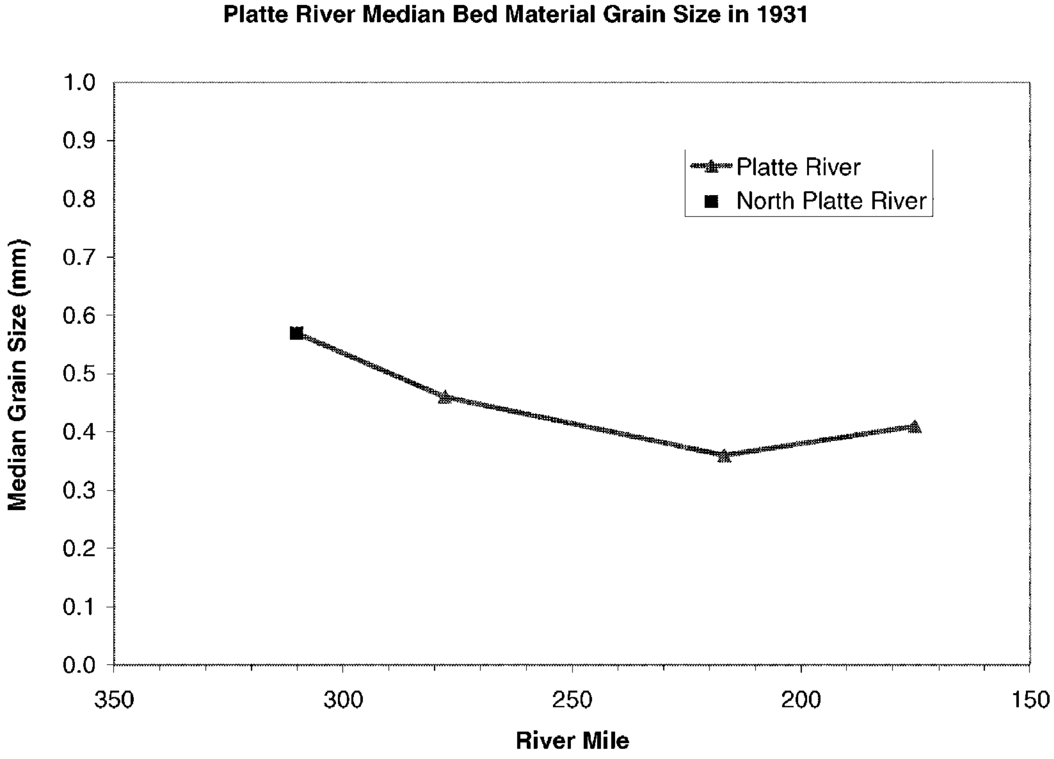

Figure 7.5. Platte River, Nebraska, median grain size along this braided river channel in 1931.

7.3.6.5 Sediment-Discharge Rating Curves

Sediment-discharge rating curves connect the river hydrology to sediment transport. Sediment rating curves are usually developed by measuring the depth-averaged, suspended sediment concentration and flow rate for a large number of vertical lines across a river channel at a stream gaging station (Edwards and Glysson, 1988). The suspended sediment load for the cross section is calculated by multiplying each average concentration by the flow rate corresponding to its vertical and summing over the cross section. Infrequently, bedload is measured across the channel. However, if the bedload is not sampled, it is sometimes computed using the modified Einstein Procedure (Colby and Hambree, 1955) or estimated at 2 to 15 percent of the suspended load (Strand and Pemberton, 1982). In either case, the bedload is added to the suspended load to calculate the total sediment transport at the cross section. The flow rate measured for the cross section is the sum of the flow rates for each vertical. The sediment transport rate and the flow rate define one point on the sediment-discharge rating curve. The sediment rating curve is developed by repeating this procedure many times to achieve the widest range of flows possible.

Typically, there is considerable scatter among the points on a sediment-discharge rating curve. Figure 7.6 shows measured discharge and sediment concentration and a best-fit, log-log sediment rating curve through the data. This best-fit curve can be used directly with the flow-duration curve to produce a sediment-transport duration curve, but that application is biased (Gilroy et al., 1990). The bias arises when the sediment load in real units is calculated from the log-log curve, and, therefore, a retransformation bias correction is often applied (Cohn, 1995).

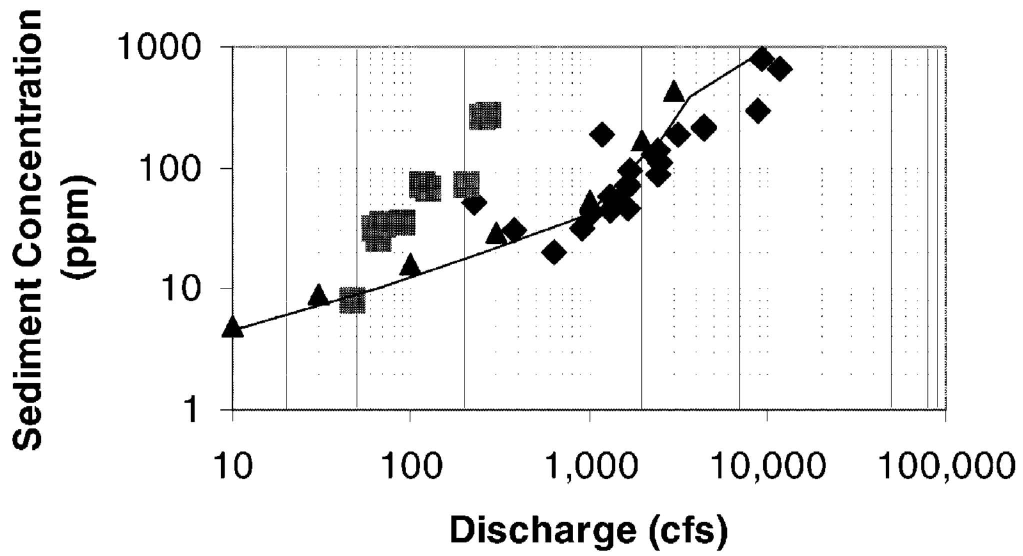

Figure 7.6 Suspended sand rating curve of the Platte River at Overton-Grand Island, Nebraska.

Seasonal differences associated with the annual cycle of runoff may require separate sediment rating curves for each season. Because of its slow nature, snowmelt typically erodes less sediment from the watershed than rainfall, especially thunderstorms and tropical cyclones. Different rating curves are often used for the snowmelt and thunderstorm seasons (Miller, 1951).

Additional variation in a sediment rating curve can occur if the supply of sediment to the riverbed is limited by a more irregular cause than a simple seasonal change. The erosional patterns of a watershed can vary greatly with landslides, fires, or other land use changes (such as grazing), which cause changes in the sediment supply to the downstream river channel.

When the suspended sediment concentrations and bedload samples are measured, the grain-size distributions of each sample can be developed to see if the samples have uniform grain sizes with standard deviation of less than 1.3. If the moving sediments are not uniform, then sediment-rating curves for each grain size can be developed. Because this level of detail is not frequently needed, the typical sediment rating curves do not distinguish among grain sizes.

Many times sediment rating curves are needed but data are not available. In those cases, an alternative is to use a predictive sediment-transport formula to estimate the sediment load for a given discharge and then develop the sediment rating curve.

7.3.6.6 Reservoir Sediment Outflows

Sediment transport downstream from dams is affected by reservoir sedimentation and hydrologic change caused by the dam and reservoir. The amount of sediment passing though a reservoir is highly dependant on the reservoir's life stage. When a large storage reservoir is first built, virtually no sediment is transported through the reservoir. All but the finest material will be deposited in the reservoir. Under these circumstances, water released from the dam can be assumed sediment free (Simons and Sentürk, 1992). As reservoir storage capacity is lost through reservoir sedimentation, and sediment is deposited near the outlet works, sediment outflow from the reservoir will increase. A typical response to dam construction and the rapid decrease in sediment supply is for the channel to degrade and armor if enough coarse material is present in the bed. Channel bed degradation allows the river to decrease its slope and sediment transport capacity in response to a decrease in sediment load. When the reservoir fills and sediment supply to the downstream channel increases, there may or may not be a noticeable channel response. Channel changes are often abrupt and difficult to predict. A possible response would be for the river to aggrade until the slope is steep enough to transport the additional sediment.

Sediment transport is also affected by the change in hydrology caused by the dam and reservoir operations. Peak flows are often reduced after dam construction (Julien, 2002) and sometimes there is even a reduction in the volume of water released into the channel due to diversions. In these cases, there is lower sediment transport capacity to transport the sediment in the channel, whether it is the beginning or end of the reservoir life cycle. In any case, the amount of sediment delivered to the channel downstream from a dam depends on the reservoir sediment trap efficiency and the configuration of the outlet structures in the dam. The ability of the channel to move that sediment, or sediment supplied from downstream tributaries, will depend on the amount and timing of releases from the dam.

7.3.6.7 Scour and Degradation

Rivers often experience changes in bed elevation. These changes can be caused by man or occur naturally. Whatever the cause, there are three generally accepted forms of bed elevation change: aggradation or degradation, general scour, and local scour (Simons and Sentürk, 1992). Aggradation and degradation are long-term processes that take place over long reaches. Bed level changes associated with aggradation or degradation are often related to changes in sediment load. General scour or contraction scour is often caused by a narrowing of the river that locally increases the velocity in a short reach. This type of scour can also occur during a flood where the bed scours on the rising limb and fills during the falling limb. Local scour is much more complicated than other forms of bed elevation change. Local scour is the removal of material near or around structures or channel obstructions (Simons and Sentürk, 1992). Another distinction is that local scour is caused by secondary flow currents that are directed toward the bed. This type of flow is difficult to model and requires complex three-dimensional models to describe the flow phenomena. Local scour is most easily estimated by using an equation developed specifically for a given structure (pier or abutment) and configuration. Bend scour exhibits characteristics of both general and local scour. There is often a decrease in width and an increase in velocity through a bend but the bend curvature creates secondary currents that are directed toward the bed and banks. Two good sources for additional information on bed level changes are *Computing Degradation and Local Scour* (Pemberton and Lara, 1984) and *Sediment Transport Technology Water and Sediment Dynamics* (Simons and Sentürk, 1992).

7.3.6.8 Sediment Transport Equations

When sufficient sediment and hydraulic data are available, sediment transport equations (see Chapters 3 and 4) and modeling can be very effective tools to not only better understand the existing transport capacity, but, more importantly, to predict how the existing system would respond to restoration options that alter the balance of sediment and flow, or the geometry of the channel. A variety of sediment equations and models are available, and research is always ongoing to improve the capabilities in this discipline. A discussion of available tools and data collection techniques is provided in Chapter 9 of this document.

7.3.6.9 Sediment Considerations for Stable Channel Design

Stable channel design parameters include the discharge capacity at low flow, bankfull flow, and floodflow; the channel width, depth, and slope; and the long-term sediment load. Discharge considerations alone are not sufficient. To be stable over the long term, the design must also take into account the river's sediment load. If the channel's sediment transport capacity is less than the incoming sediment load, channel aggradation and, possibly, bank erosion will occur. If the channel's sediment transport capacity exceeds the load of incoming sediment, channel degradation (erosion of the bed and banks) will occur. Increased sinuosity and river meandering may also result under the condition of excessive transport capacity.

A unique channel design can be determined by using the minimum rate of energy dissipation theory (Yang, 1976;, Yang and Song, 1979, 1984; and Yang 1996). This theory states that when a dynamic system reaches its equilibrium condition, its rate of energy dissipation is at a minimum. The minimum depends on the constraints applied to the system; in this case, water discharge, sediment load, channel roughness, and, possibly, the valley slope. For a uniform flow of a given channel width where the rate of energy dissipation due to sediment transport can be ignored, the rate of energy dissipation per unit weight of water is:

$$\frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = VS = \textit{unit stream power} \tag{7.4}$$

where Y = potential energy per unit weight of water,
V = mean channel velocity, and
S = channel slope.

Thus, the theory of minimum unit stream power requires that VS = minimum. The integration of VS across the channel will yield $Q_w\ S$, which is also equal to a minimum. The following four equations can be utilized for stable channel design:

1. Continuity equation

$$Q_w = VA \tag{7.5}$$

where Q_w = water discharge in the channel,
V = channel velocity, and
A = cross-sectional area of flow.

2. Manning's equation

$$V = \frac{1.486}{n}\left(\frac{A}{P}\right)^{2/3} S^{1/2} \tag{7.6}$$

3. A sediment transport function

$$Q_s = f(V, S, A, P, D, d, \nu, \omega) \tag{7.7}$$

where Q_s = sediment load,
P = wetted perimeter,
D = water depth,
d = sediment particle diameter,
ν = fluid viscosity (primarily a function of water temperature), and
ω = particle fall velocity (primarily a function of the diameter, shape, and density of the sediment particle and of the fluid viscosity).

The chosen sediment transport equation needs to be verified or calibrated with measured hydraulic and sediment load data.

4. Minimum unit stream power

$$VS = \text{minimum} \tag{7.8}$$

The known terms are Q_w, Q_s, n, d, ν, ω. The unknown terms are V, S, A, and P and can be solved by solution Equations (7.5) through (7.8). The bankfull channel width, computed from these four equations, should be checked for reasonableness with one of the regime equations presented in Table 7.1. If the computed slope is steeper than the valley slope, then the solution must be constrained by the valley slope. If the computed slope is less than the valley slope, then the sinuosity and the degree of meandering can be computed by comparison with the valley slope. The meander wavelength can best be determined from an empirical equation as a function of the bankfull channel width such as Equation (7.9) (Leopold, 1995):

$$\lambda = 10\, W^{1.03} \tag{7.9}$$

where λ = meander wavelength, in feet, and
W = bankfull channel width, in feet.

7.3.6.10 Evaluation of Potential Contaminants

In certain instances, evaluation of potential contaminants attached to river sediments may also be required for a restoration project. This analysis is often done where mining or other historical human activities may result in uncontrolled release of contaminants into a river system. Evaluation of contaminants is of particular interest in dealing with restoration projects where old mine tailings or sediments trapped in a reservoir may be released as a result of the project, but would otherwise remain in place. Typically, sediments are tested for levels of contaminants above the natural background levels present in the river system. Samples can be collected for testing from the reservoir using a variety of methods, including drilling from barges, using divers, or performing a reservoir drawdown to access exposed sediments on the margin of the reservoir.

7.3.7 Biologic Function and Habitat

In addition to the focus on the physical characteristics of a river system, discussed in the previous sections, the impact of physical characteristics on biologic function should also be addressed in the plan or design. The biologic community is directly and indirectly dependent on the physical characteristics of a channel, and alterations to the existing condition can result in biologic consequences. This is not to imply that physical change to the river brings only negative impacts. For example, natural disturbances such as flooding are sometimes required to renew biological function and process. Physical change to the river system by man, if thoroughly considered and in accord with the natural sciences, can also promote biologic function and benefits.

Since the design or management of physical features in a river can impact vegetation, macroinvertebrates, fish, and wildlife, biologic impacts should always be considered. The statement "if you build it, they will come" can be applied to channel restoration efforts. The physical conditions constructed are the invitation to colonization by the biologic communities associated with that niche. If the desired conditions are not correctly diagnosed and replicated, biological communities can also disappear at a rapid rate. In addition to analyzing the geomorphology, hydrology, hydraulics, and sediment transport of a river system, consider the target communities or species in the project area and determine how physical features can be optimized to promote desirable habitat. Consideration should also be given to the competition among species. For example, backwater habitats may be of more benefit to some fish species than others, and the establishments of backwater habitats may help some species to the ultimate detriment of others.

Depending on the project, variables such as slope, bankfull discharge, or channel width may be fixed, but these values can often be adjusted to promote environmental qualities, since geomorphic variables usually function effectively within a range of values. When the variable is open to determination based on geomorphology, hydraulics, and sediment transport, an analysis of biologic benefit should also aid the determination. For this reason, the river restoration study team should be interdisciplinary, with biologists as key members of the team.

7.4 Sediment Restoration Options

Choosing a restoration option involves not only an understanding of existing river processes, but also a determination of what the desired outcome of the project will be. The following discussions present some ideas for determining which restoration options will be considered for a project based on the goals and objectives of the project, the range of feasible options available for implementation, and some examples of options that have been utilized on other rivers.

7.4.1 Goals and Objectives

Restoration goals and objectives are most useful when they are expressed in terms of the final desired outcome, rather than in terms of a possible solution to achieve that outcome. For example, a restoration goal of significantly improving spawning habitat for a certain species of fish is more helpful than a goal of achieving a certain minimum flow. The minimum flow might help achieve the larger goal, but it may not be the right flow or make enough of a difference by itself. A restoration goal of allowing a meandering river channel to migrate across its flood plain, at some natural rate, is more helpful than prescribing a single meander amplitude for all locations.

Restoration projects should be consistent with natural processes in order to be sustainable. For example, streambank stabilization could be considered a restoration project if bank erosion were caused by some human disturbance, such as the redirection of flow velocities from an eroding bank by some upstream structure. However, river channel migration is a natural process and streambank erosion is common on the outside of meander bends. In some cases, the rates of channel migration have been accelerated by human disturbance, such as the clearing of riparian vegetation. Bank stabilization in this case would be consistent with natural processes if the stabilization project were designed to slow the rates of channel migration back to more natural conditions. The complete prevention of channel migration across the flood plain is not consistent with natural processes and would likely incur long-term maintenance costs.

Restoration projects often work best when they can treat the disturbance at the source. In some cases, the source can be fairly local, but in other cases the source of the disturbance may be far upstream. If the disturbance cannot be treated at its source due to legal, institutional, or economic reasons, then a restoration goal might be to help the river achieve a new equilibrium.

Technical understanding of the causes of the disturbance and the possible range of solutions can significantly alter the restoration goals and objectives. During the early 1980's, the general understanding amongst resource managers at Grand Canyon National Park was that sandbars along the Colorado River were destined to erode over time. Therefore, the management goal was to focus on slowing the rate of eventual erosion. After additional study (U.S. Department of the Interior, 1995), it was determined that the objectives of the restoration plan could be expanded from slowing the rate of erosion, to the sustainable maintenance of the sandbars along the river through altered flow management. A similar expansion of the objective, based on technical investigations, occurred in conjunction with the Platte River in Nebraska. Resource managers from the U.S. Fish and Wildlife Service were concerned about narrowing of the Platte River channel, and the initial objectives focused on restoration programs for slowing the rate of narrowing. Further studies (Murphy and Randle, 2003) indicated that an objective of some channel widening was possible with a concerted restoration plan for flow and land management actions.

7.4.2 Fully Assess the Range of Options

The following topics are proposed for consideration when formulating conceptual alternatives at the onset of a restoration project. Later in the restoration project analysis, these topics can help to produce a wider range of viable options or aid in identifying nonfeasible solutions.

7.4.2.1 Sediment and Flow

Both sediment and flow should be considered when searching for feasible solutions. There is a greater general awareness of the direct impacts that result to the channel, both physically and environmentally, from the manipulation of flows. What are less frequently taken into consideration are channel changes resulting from disturbances to the sediment transport regimen. A good restoration alternative should address both concerns. Stable channels can be planned using the procedures presented under the section 7.3.6.9.

7.4.2.2 Local Versus System-wide

An important step in the preliminary stages of a restoration project is to identify whether the problem is local or system wide, and match the solution to the scope of the problem. River processes, including sediment transport, are in general system-wide. However, many problems are treated locally, and the treatment may or may not be effective in fixing the problem.

For example, a local problem may be a short reach of riverbank where erosion has been induced as a result of a bridge located just downstream of the riverbank. It may be desired to limit additional bank erosion in order to control the alignment of the river as it approaches the bridge. In order to treat this problem, the first step would be to verify that the erosion is indeed localized and due to the bridge, rather than a reaction to a system-wide impact. Then, an effective solution can be generated to limit additional erosion of the bank, as long as potential impacts from implementing the solution are understood. For instance, the solution to the local bank erosion problem should not induce bank erosion on the opposite riverbank.

On the other hand, a bank erosion problem in a river tributary, resulting from bed degradation, could be a system-wide problem if the degradation resulted from a migrating head cut triggered by base level lowering in the main channel. A grade control structure in tandem with bank protection, both local solutions, may be sufficient for this system-wide problem. However, a full assessment would be needed to determine the causative factors for the head cut, anticipate the measure of future degradation, and incorporate these conclusions into the design of the grade control structure.

Streambed and bank erosion resulting from a reduction in sediment supply, or an increase in clear water discharge, from the upstream watershed is also a system-wide problem. In this case, a localized solution, the installation of bank protection, would be ineffectual and probably require costly maintenance. One preferred option might be an action plan that re-establishes the transport of sediment in the channel through changes in watershed management.

Increased sediment loads, causing system-wide problems, can result from sources such as bank erosion, a rejuvenated headcut on a tributary stream, or land clearing and development. Sedimentation problems can also be caused by the diversion of water from the stream without the corresponding diversion of sediment. Solutions can be local or system wide. The eroding high bank or rejuvenated tributary headcut could be stabilized locally. Depending on the problem, a system-wide solution might call for vegetated buffer areas along streambanks in a watershed to reduce the sediment supply to downstream reaches. When possible, annual discharges of high flows for a short duration, which do not produce negative flood impacts, can help move sediment from an aggrading reach. Potential solutions in urban areas might call for legislation requiring sediment traps on storm water systems or revised maintenance programs for winter road sanding operations.

7.4.2.3 Natural Versus Restrained Systems

Although the goal may be to fully or partially restore natural processes, restoration projects are often faced with the question of whether to incorporate features that limit channel migration and bank erosion to protect infrastructure and property. A restrained system is defined as a river with bank segments that are fixed to an existing position through the use of erosion-resistant materials, such as riprap. In cases where bank erosion is occurring, this is often perceived initially as the favored option to limit further bank erosion. However, when reviewed over the long term, hardening banks may be the less desirable option because it can generate negative consequences on river processes. For example, when banks are hardened on low elevation surfaces within the channel migration zone; this can limit natural channel migration and development of side channels.

When implementing restoration projects, it is important to assess whether long-term interests are best served by solutions that restrict the channel and flood plain, or by solutions that allow for a river to function in a more natural dynamic equilibrium. When viewed through a short window of time, restraining the flood plain or hardening the riverbanks may appear to be a good option. However, this option can be costly when maintenance and environmental costs are projected over the long term. Increases in the percentage of restrained bank tend to lead to a larger and greater complexity of problems for the river system over the long term. Such problems can include the failure of bank protection, channel instability on the opposite riverbank or the downstream river channel, and the limitation of natural channel migration.

Before accepting a restraining solution, determine if there is a feasible and cost-effective solution that allows the channel to migrate within the natural channel migration zone. The range of alternative solutions is as broad as the range of problems and could include levee setbacks, new flood plain zoning, watershed-wide management approaches, road or structure relocations, natural channel relocations, flow-diversion structures, property acquisition, or construction of longer bridge spans across the river channel.

7.4.2.4 Monitoring Versus Modification

Not all problems require immediate action. In some situations, a monitoring program may be a feasible and effective alternative to action-based solutions. Geomorphic assessments, risk analysis, probability studies, and cost-benefit ratios may indicate that a monitoring program, combined with simple actions only required during or after high flows, could be the preferred alternative. Adaptive management is a more sophisticated version of the monitoring alternative and is addressed in section 7.4.6.

Some general rules for implementing an effective monitoring program are listed below:

- Design the program with specific goals and objectives in mind.
- Make predictions about the parameters that are to be monitored.
- Limit the monitoring to repeatable procedures.
- Use quantitative measures of such things as bank erosion, channel width, bank height, and bed-material grain size.
- Take photographs and document the locations where the photographs are taken.
- Be realistic about the windows of time when field visits are practical and productive. For example, manual data collection during peak flow events is difficult to do safely.
- Design and incorporate adequate analysis time and labor costs with a framework for triggering decisions and needed actions.

7.4.3 Restoration Treatments

The previously discussed conceptual model and analysis tools provide a basis for making decisions on how to restore natural channel processes as part of accomplishing restoration project objectives and goals. Some common strategies that can be implemented and their relationship with restoration of sediment processes are discussed below.

7.4.3.1 Restoration of the Historic Channel Migration Zone

As discussed previously, the historic channel migration zone boundary has the potential to expand in the future where the boundary is composed of erodible material and is subjected to lateral erosion from the river during floods. In undeveloped areas, the rate of this expansion can be limited by old growth trees on terrace surfaces that protect the bank when the roots reach the interface between the bank and the water surface. In areas impacted by human development, clearing of the vegetation adjacent to the historic channel migration zone can accelerate the rate at which the historic channel migration zone boundary expands if the boundary is composed of erodible material such as alluvium or glacial outwash. Also, logging of the riparian flood plain within the historic channel migration zone can accelerate the rate of channel migration and erosion. Vegetation on bars normally dissipates energy (and water velocities) between the main channel and the boundaries of the historic channel migration zone. When it is removed, the rates of channel migration can be accelerated. Potential restoration strategies to minimize future erosion where infrastructure or property needs to be protected could include deflecting the river away from the bank, setting back the infrastructure farther away from the historic channel migration zone boundary, placing engineered bank protection, or a combination of these options. Because logging and development often result in the highest potential future rates of lateral erosion, strategies to limit erosion may also include long-term land use alternatives, such as revegetating the terrace surface and preventing development within or adjacent to the historic channel migration zone.

7.4.3.2 Levee Setback and Removal

The setback or removal of levees is often one of the most effective ways to restore flood plain access in rivers. Flood protection levees cut off access to the flood plain resulting in a higher peak flow, river stage, and velocities, and increased sediment and woody debris transport rates in the main channel. Rivers confined by levees often experience erosion along the channel bottom and a coarsening of sediment sizes present on the channel bed. If there is no property or infrastructure at risk, resource managers may decide to completely remove a levee to restore the flood plain. If some level of flood control must be maintained, the levee may be set back a certain distance from the active channel. When considering a levee setback or removal, the existing sediment processes in the active channel must also be assessed to determine if any modifications need to be incorporated.

For example, on the Dungeness River in Washington, levees exist along both sides of the river for several miles near the mouth. With the higher velocities and river stage created by the levees, one would expect erosion and armoring of the river channel. However, in some places the levees cut off or constrict nearly the entire flood plain, while in other places the levees were set back in the flood plain a distance of two to three times the active channel width. Similar to a bridge constriction, where the levees create a constriction, they locally increase the flow velocities and create backwater areas upstream where sediment deposits during floods. When the elevations of the existing channel bed were compared to the 1930's conditions, up to 10 feet of sediment deposition was documented in the backwater areas upstream from the levee constrictions (Bountry et al., 2002). The sediment deposition was so great that the channel bottom is now higher than the surrounding flood plains. If these levees were set back, the sediment deposition upstream from the levee constrictions must be excavated to maintain the active channel in its historic location. Otherwise, the river channel would immediately avulse (abruptly change course) across the flood plain and onto surfaces where the active river has not flowed for thousands of years.

7.4.3.3 Roadway Setback

When roads exist along river channels in the flood plain zone, the roads can be at risk for erosion from flooding due to the natural tendencies of the river to laterally migrate. In response to this action, roadways are often protected from erosion by using bank protection, including rock, woody debris, concrete, or other manmade devices, and by building the road at a higher elevation than the surrounding ground surface. An alternative in areas where the river is known to run alongside the road is to set back the road and restore the natural riverbank. Ideally, a road should be set back as far away from the river and flood plain boundaries as possible, preferably on a higher, older surface that is not likely be subjected to erosion in the near future. However, placing the road onto a steep hillside may actually initiate slope failures and cause additional sediment erosion issues. The benefit of road setback versus long-term bank protection maintenance costs and impacts on river processes at the existing site must be evaluated on a site-by-site basis.

7.4.3.4 Lengthening Bridge Spans

A bridge may be located at a natural geologic constriction and have a very limited impact on channel processes. However, in many cases, bridge spans constrict the natural channel width, causing a local increase in velocity, river stage, and sediment transport through the bridge and a backwater effect and depositional area upstream of the bridge. The impacts from a particular bridge typically do not expand upstream and downstream more than several channel widths. Additional bank protection in the vicinity of the bridge or other structures, such as levees, will increase the extent of effects on channel processes. When bridges are constricting the river channel and causing localized undesired impacts, a restoration option is to lengthen the bridge span and reduce the number and width of piers in the wetted channel. An analysis should be done to determine how bridge lengthening will meet project goals and what the effects on hydraulic and sediment processes will be.

Questions that should be addressed regarding modifications to bridges include:

- Is the existing bridge located at a natural geologic constriction or does the existing bridge cut off historical channel paths or flood plain?
- What will be the new slope of the river channel through the reach?
- How will sediment transport through the reach change?
- Does the bridge deck need to be raised because of expected deposition or will sediment transport through the reach remain high?
- If flooding is currently an issue, will the bridge lengthening alone be sufficient enough to reduce upstream river stage to an acceptable level during high flows?
- Does there need to be any channel modification or design work done in coordination with a bridge expansion project?

7.4.3.5 Side Channel, Vegetation, and Woody Debris Recovery

Side channels are an important resource in a natural river system for providing aquatic habitat. It may also be desired to restore side channel habitat as part of the restoration of flood plain or historic channel migration zone areas. For instance, consider a levee or road embankment that has been constructed such that it cuts off historical side channel connections with the main channel. If the restoration project is to set back the levee or road, side channels could be constructed in the setback area to speed-up the recovery of natural processes. As part of the recovery process, woody debris could also be incorporated if it was traditionally part of the natural system but was currently absent due to higher transport capacities from the constricted levee reach or historical removal.

Side channels are old channel paths of the main river channel and may one day contain the main channel again. Therefore, restoration designs of side channels are more likely to be successful if they can follow the historic paths of the main channel. Historic aerial photography, maps, and surveys of the river corridor, prior to disturbance, can provide an excellent guide for side channel design. Also, geomorphic field mapping of these historic channel paths likely will be necessary. Large woody debris may need to be placed at the upstream entrance to side channels to prevent the main channel from easily overtaking the side channel.

Recent research has shown that vegetation and woody debris can be a critical component in maintaining a natural rate of channel migration by stabilizing banks within and on the boundaries of the channel migration zone (Beeson and Doyle, 1995; Collins and Montgomery, 2002). When vegetation has been cleared on terrace surfaces adjacent to the channel migration zone, the terrace banks often experience high rates of erosion during floods, putting infrastructure and property at risk. When vegetation and woody debris have been cleared within the channel migration zone, the channel may become unstable and migration rates accelerated. Vegetation recovery efforts can restore the natural roughness in the channel and flood plain. This re-establishes slow velocity and energy dissipation in areas that would otherwise be subject to high velocity and larger volumes of runoff during floods. Recovery of native vegetation is often more aesthetically pleasing and considered a more natural solution to erosion and instability. While vegetation recovery can take longer than many other restoration strategies to be fully implemented, it can be combined with other restoration options to maintain more stability over the long term.

7.4.3.6 Changes to Channel Cross Section or Sizing

Deep, narrow channels provide efficient flow conveyance systems, but they are subject to higher erosive forces and often require hard channel linings. In these cases, sediment transport capacity may exceed the supply of sediment. In populated areas, channels are often confined and made deeper to enhance floodflow conveyance. To reverse that process in a restoration project, the hard lining of channel banks can be removed to allow the channel to adjust to new conditions over time, or a new channel cross section could be constructed to speed up the process.

A common natural channel configuration is a meandering thalweg path (deepest point in the channel) within the channel banks. The channel banks are not necessarily stable, but often migrate slowly over time within the flood plain. This configuration can be described as a staged design, including the low-flow channel (smallest) which is contained within the larger bankfull flow channel, which is, in turn, contained within the larger flood plain. As flows increase the wetted width increases and water overtops banks from one channel into the next larger channel. This staged configuration allows flows to spread out during floods and keeps flow depths and erosive forces in the main (low flow) channel at minimal levels. This also keeps smaller flows concentrated within the low-flow channel to maintain efficient sediment transport and biologic benefit. The natural channel will evolve to this configuration in the absence of geologic or anthropomorphic constraints until natural vegetation in the overbank areas is sufficient to withstand the erosive forces and protect the overbank from erosion.

If the channel is constructed with a simple, over-wide trapezoidal geometry, sediment transport capacity may be less than the incoming supply of sediment. Under this condition, sediment will settle out in the areas of lowest flow velocities, and, over time, will create the complex geometry of a low-flow channel, effective flow channel, and overbank terraces.

The complex channel configuration does not require costly bank protection and, for biologic benefit, offers a wider range of habitat niches over a greater spatial area. It also helps to promote the balance of sediment supply and transport. A drawback to this treatment is that a large amount of land is required to develop the active stream corridor. This land may serve dual uses, but the uses must be flood tolerant and adaptable to occasional channel migration. For instance, using the land for agricultural purposes may have a low risk of flood damage, and the land could actually benefit from periodic inundation. On the other hand, it would be a high risk to build residences in this area that could be damaged or put people in danger during floods.

7.4.3.7 Changes to Channel and Flood Plain Roughness

The roughness of the channel or flood plain has a strong influence on flow conveyance capacity and sediment transport. The management of roughness characteristics within the flow corridor can serve as effective restoration techniques. Grasses and other vegetation, which bend over easily during high flows, offer lower flow resistance, provide greater flow conveyance, and may be subject to higher erosive forces. Structures and substantial growths of vegetation on the flood plain, including trees and stiffer shrubs, increase roughness, decrease flow conveyance, and reduce the average erosive force acting on the flood plain. Vegetation on channel banks increases roughness, reduces velocity and shear stresses along the bank, and can be used at some locations to encourage sediment deposition for bank stabilization. Native riparian species of vegetation may be planted in the flood plain to restore the natural roughness. This vegetation may require some protection from people, floods, and grazing animals until it becomes established.

7.4.3.8 Bank Stabilization Concepts

Bank stabilization has historically been constructed on a reactionary basis in response to lateral erosion of banks from floods. There are several manuals that discuss streambank stabilization methods, such as the *WES Stream Investigation and Streambank Stabilization Handbook* (Biedenharn, 1997). An important point brought up in the manual is that "too often river engineers and scientists may be pressured by circumstances beyond their control to plan and construct riverbank stabilization works too quickly, without adequate time or resources for a conceptual evaluation of the problem." (Biedenharn, 1997). By following the steps outlined in this chapter, it is hoped that a better understanding can be gained of how proposed bank stabilization may or may not work with natural processes prior to installation.

The impact of bank stabilization on natural processes depends on the location of the bank relative to the channel migration zone boundaries, the rate of natural channel migration, and the material that composes the bank stabilization. Traditional bank stabilization uses hard, angular rock that protects against the high velocities and shear stress against the bank.

Stabilizing banks within the channel migration zone (using any type of material) has the biggest impact on altering natural channel dynamics and, where possible, should be avoided in restoration projects. Stabilizing terrace banks along the boundaries of the historic channel migration zone would have minimal impact on channel dynamics. Softer types of bank protection may be considered to better mimic the natural rates of channel migration. Softer bank protection can incorporate revegetation, root wads, geotextiles, and a number of other combinations that create a deformable rough surface and dissipate energy.

Another solution to bank stabilization may be to design structures that are tied into the bank and extend into the river channel to deflect the thalweg and high velocities away from the bank. Bend-way weirs and engineered logjams are two examples that are becoming more popular (Derrick, 1998; Abbe, 2000). These types of structures not only provide protection to banks, but structures using native materials are also aesthetically pleasing and develop aquatic habitat by forming cover and scour pools utilized by fish.

7.4.3.9 Grade Control Structures

Grade control features can be placed across the river channel to prevent head-cutting in degrading channels or to build up the bed of an incised stream to match an upstream riverbed elevation (Federal Interagency Stream Restoration Working Group, 1998). They work by providing a "hard point" in the riverbed that resists erosion forces and reduces the upstream energy slope. These types of structures work well in areas where the structure can be keyed into the banks and the channel cannot outflank the structure. Originally, grade control structures were built in a straight line perpendicular to the riverflow. Recent variations have incorporated "V" and "W" shaped structures to not only control the grade, but to direct the thalweg of the riverbed toward the center of the stream. This variation helps redirect erosive stream forces away from the banks of the river. The structures are typically composed of rock, steel sheetpile, wood, or a combination of these materials. Fish passage and aquatic habitat can be integrated into the structure if designed and sited properly. If improperly designed, the structure can become a fish passage barrier, can result in significant downstream scouring, or can cause upstream meandering that will result in the river outflanking the structure.

7.4.3.10 New Channel Design and Relocations

In the last few decades, there has been a growing awareness of the impacts from historic approaches to river-engineering problems undertaken in the early to mid-1900's. Historically, management goals were focused on increasing navigation and flood conveyance, providing access across rivers, and providing protection to adjacent development and infrastructure from flooding. Potential long-term impacts to river processes from these activities were not generally considered or understood. In many areas, these activities resulted in extensive environmental impacts. In recent decades, society began to place more value on the natural environment. Because of past impacts and society's changing values, restoration approaches that work with natural river processes and enhance or restore habitat have become part of the management objective. In highly disturbed rivers, these approaches may still require substantial construction work in the river corridor, but the outcome is a channel that more closely mimics and works with natural processes.

Natural channel construction and relocation projects are gaining wider acceptance as our understanding of the river as a multi-purpose system continues to grow. Advancements in the fields of geomorphology, sediment transport, botany, fisheries, stream aquatics, and water quality have pointed to the importance of environmental factors and their interrelations. Although natural channel relocations or construction can offer many environmental benefits, their design is complex and should not be attempted based simply upon hydraulic designs for conveyance channels. The following list of design manual references for natural channel construction is offered to encourage thorough designs. The publishing dates of these references illustrate how recent this science and design methodology is:

- Biedenharn, Elliot, and Watson (1997)
- Copeland, et al.(2001)
- Federal Interagency Stream Restoration Working Group (1998)
- Inter-Fluve, Inc. (1998, 1999)

One shortcoming still found in some of the manuals listed above is the overreliance on "hard" protection in the upper banks of rivers. Materials such as riprap, concrete blocks, and other non-natural materials restrain the channel bank and prevent future lateral adjustments. Hard banks are a legacy from hydraulic conveyance channel design techniques of an earlier period. Stream corridors, natural channel geometry, and the informed use of vegetated bank protection techniques are more challenging to incorporate into the design, but they frequently offer the greatest environmental benefit and are most feasible over the long-term. A second common shortcoming to be avoided is to attempt natural channel construction without sufficient analysis and design of the system.

The complete design of a natural channel is beyond the scope of this manual, however the most important sediment transport consideration for a stable channel is "sediment in should equal sediment out" of the design reach. Yang's theory of minimum total stream power and unit stream power (presented in section 7.3.6.9) provides guidance on this rule. In many instances, this consideration will form the basis for the channel design.

7.4.3.11 Special Flow Releases From Dams

Downstream from dams, river channels are subject to a variety of impacts (Collier et al., 2000). In some cases, clear-water releases subject the downstream river channel to degradation, armoring, bank erosion, and increased sinuosity. In other cases, so much water is diverted from the downstream river channel that sediment from downstream tributaries aggrades the river channel, decreases sinuosity, and increases the rates of lateral migration.

One potential restoration tool for these downstream river channels is the scheduling of short-duration, high magnitude flows from the dam for a variety of purposes. For example, an experimental "beach-habitat-building flow" was released from Glen Canyon Dam during 7 days in March and April 1996 to rebuild sandbars along the Colorado River in the Grand Canyon (Webb et al, 1999). The beach-habitat-building flow increased riverflow from a normal fluctuating range between 5,000 and 20,000 ft^3/s to a steady 45,000 ft^3/s for 7 days. Low steady flows of 8,000 ft^3/s were released from the dam for 3 days prior to, and just after, the high steady flow, so that measurements could be easily conducted both before and after the experiment. Measurements were also conducted during the high steady flow. The experimental beach-habitat-building flow was highly successful in rebuilding sandbars throughout the river corridor in Grand Canyon, and about half the volume of sand deposited during this experiment still remained after 2 years.

For the Trinity River in California, short-duration, high steady flows have been proposed to temporarily mobilize the gravel-bed sediments and flush fine sediments from the gravels. Although upstream reservoirs trap nearly all of the upstream sediment supply, the reservoirs also reduce the annual flood peak, and fine sediment supplied from downstream tributaries has deposited on river gravels. The deposition of fine sediment on the river gravels reduces their suitability as fish spawning areas.

Short-duration, higher magnitude flows have been proposed for the Platte River in Nebraska to temporarily mobilize the riverbed to scour seedling vegetation and build sandbars for nesting birds (Murphy and Randle, 2003). Endangered birds that use the Platte River require wide, shallow, active channels, with wide open views that are unobstructed by vegetation. Annual peak flows have substantially reduced over the 20th century, in response to water resource development, and active channel widths and the associated open view have also decreased. Restoration plans call for mechanically clearing mature vegetation from selected areas and using short-duration, high releases from an upstream reservoir to annually scour seedlings.

Special flow releases from dams might also be used to increase the sediment transport capacity of the downstream river channel if sediment aggradation is a problem. Minimum releases to the downstream channel and limits on the rate of flow change may also have benefits for the aquatic ecosystem. For example, minimum flows will ensure some minimum level of aquatic habitat.

Limits on the rate that flow is decreased may help prevent the stranding of fish and seepage-based bank erosion. Limits on the rate that flow is increased may prevent injury to people that may be in the downstream river channel.

7.4.4 Biologic Function and Habitat

When using restoration treatments, consider their effect on the biologic function and habitats of the study reach. Such considerations include the channel cross-section shape, channel banks, channel planform characteristics, changes in channel grade, and flow and sediment designs.

7.4.4.1 Channel Cross-Section Shape

One of the most fruitful examples of habitat enhancement is the conversion of a conveyance channel to a natural channel. The geometric shape of a channel cross section heavily influences on biologic function. A conveyance channel is a highly efficient structure for transporting flow, yet it provides virtually no habitat that promotes biologic diversity. If the channel is constructed or managed with an emphasis on morphologic processes, more diverse and sustainable habitat for the biologic community can be generated.

A conveyance channel is normally trapezoidal, with a small width to depth ratio and hardened, steep sidewalls. Velocities are relatively high and consistent in the cross section and the profile, and most flows are contained within the channel. Steep walled conveyance channels are not easily accessible to the terrestrial biologic community, and the hard linings, required to protect against erosion, substantially reduce the development of riparian and fishery habitat. In northern Colorado and at other locations, deer attempting to reach water in concrete lined canals occasionally fall in and become trapped by the steep concrete walls. Atlantic salmon in Lake Michigan are hampered in their migration up concrete lined streams by the lack of slow velocity refuge areas. In contrast, the irregular bed of a natural channel offers resting pools and eddies where the salmon can shelter between bursts of greater swimming effort. In concrete lined channels, only the largest and strongest of the species can negotiate extended lengths of smooth channel, and even minor velocity variations at joints between the poured concrete are utilized for the passage.

In addition to an irregular bed, a natural channel provides refuge areas in a variety of flows by incorporating a low-flow channel, larger bankfull channel, and flood plain areas. The terrain and soil conditions are varied; moisture conditions and vegetation change with respect to proximity to the low-flow channel, and velocity and erosive conditions within the channel are lower and more variable in cross-section and profile. All aspects of a natural channel lead to a greater variety of niches for biologic communities. In particular, the streambanks support riparian vegetation that serves as a border between a terrestrial and aquatic habitat. This is classified as an "edge" habitat that sustains a particularly diverse range of wildlife.

7.4.4.2 Channel Banks

In areas with cohesive soils, steep and undercut banks in the outer bends of rivers offer multiple benefits, including habitat for fish, thermal cooling, and more vegetative material entering the system for macroinvertebrates. Fish lunkers, more commonly seen in the Midwest, are employed to mimic this beneficial habitat. Fish lunkers are cells constructed of heavy wooden planks and blocks, which are embedded into the toe of the streambanks at the channel bed level (Federal Interagency Stream Restoration Working Group, 1998). These structures provide shaded aquatic habitat and help prevent streambank erosion. In small stream systems, coarse or irregular stream beds and banks help to trap floating vegetation, thereby facilitating partial decomposition by macroinvertebrates which, in turn, fuels the stream ecosystem. Logjams and brush piles along the banks offer similar benefits. In addition, logjams and brush piles provide backwater and flow velocity diversity, which creates additional habitat niches. A movement in the mid-1900's encouraged the removal of all woody debris and jams from rivers for the sake of increased flow conveyance. However, natural logjams can still be found in many areas of the country, notably in the Pacific Northwest, where the construction of logjams for habitat generation and bank protection is also gaining support. In general, the number of fish a stream can support is a function of the available habitat produced by banks, logs, brush, boulders, and pools.

7.4.4.3 Channel Planform Characteristics

Wide, shallow channels provide habitat for a different biologic community than a narrow and deep channel configuration. Braided channels with higher sediment loads may be desirable for specific species. On other projects, backwaters and large pools could be the goals. In general, pools are desirable fish habitat and aid fish survival during periods of drought or extreme temperatures. A deeper pool offers more fish habitat and cooler water temperatures during hotter summer months. Therefore, the number and size of fish often increase with pool depth. Shallow flow depths have the potential to increase water temperatures and expose more fish to predators. Both results could be considered detrimental or beneficial, depending on the biologic community to be served. Interconnected lakes serve as desirable rearing habitat for sockeye salmon and attract migratory wildfowl. In the Rocky Mountain region, overbank areas that are periodically flooded provide riparian and wetland habitat, while steeper draining banks may be beneficial as upland browse for deer and elk. Along the Platte River in Nebraska, wide shallow channels without vegetated river islands are desirable habitat for migratory birds. In some cases, there are conflicting habitat needs among various species, especially when non-native species are present. Therefore, restoration planners may have to choose how to balance the competing habitat requirements.

7.4.4.4 Changes in Channel Grade

Profile breaks or grade controls can be barriers to fish passage and a negative consequence for desirable migratory salmonid fish in the Northeast, Northwest, and Alaska. However, a grade break can also be beneficial. An abrupt change in the channel grade can help to separate native and introduced fish species, such as the brown trout and rainbow trout in Colorado. The native brown trout remain only in the furthest upstream reaches of steep gradient streams, while the introduced rainbow have dominated and eliminated natives in the majority of downstream reaches. The configuration of the grade break needed to serve as a barrier is species dependent. An adult king salmon can negotiate grade breaks several feet in elevation, while smaller pink salmon cannot.

Grade breaks can also be beneficial in warm shallow systems by boosting depleted oxygen levels, providing mixing for water quality. In urban or park settings, grade breaks can increase audible and aesthetic values near pedestrian walkways. They can also provide areas of varying velocity that provide additional habitat diversity.

The construction of engineered riffles can be an effective means of providing fish and boat passage where a grade control structure or dam is needed. The engineered riffle is effective because it provides fish passage over the entire width of the channel. The slope of the riffle is generally less than 2 percent, but the required value is dependent on the fish species. For boat passage, special consideration is needed to provide navigable depths and the avoidance of strong hydraulic jumps.

7.4.4.5 Flow and Sediment Designs

Physical conditions that impact biologic function include not only geometric parameters, but also flow and sediment conditions. Options in flow regulation could also significantly impact species. For example, after the construction of storage reservoirs in the Platte River basin, peak riverflows along the Platte River in Nebraska are now about the same magnitude, whether they occur from the spring snowmelt in the Rocky Mountains or from summer thunderstorms in the Nebraska plains (Murphy and Randle, 2003). Therefore, sandbars that are deposited by the river during the reduced spring flows tend to be lower in elevation and are more easily inundated during the summer thunderstorms. Birds that attempt to nest on these sandbars in late spring may have their nests inundated by summer thunderstorms. Endangered birds along the Platte River, including the piping plover and least tern, may benefit from a special high-flow dam release that is higher than the typical peak flow from a summer thunderstorm. If such a special flow release results in the deposition of higher-elevation sandbars, the endangered birds may be able to build nests that are not inundated by summer thunderstorms.

Channels with a high sediment load tend to have a less diverse range of biologic communities, but they often contain members that have uniquely evolved to thrive in this environment, such as the humpback chub and pike minnow in the Colorado River or the pallid sturgeon in the Platte River. Higher sediment loads reduce sunlight penetration and inhibit the growth of aquatic macrophytes. Increased sediment can impact salmonid populations by smothering eggs laid in redds. Deposition of finer sediment over gravels can also decrease the production of aquatic insects. In addition, high turbidity can make it difficult for some fish species to find food.

Sediment loads can be used to promote bank stabilization through the construction or enhancement of bank configurations that produce eddies and encourage sediment deposition.

Deposition along banks produces riparian vegetation that serves to stabilize banks directly through root growth and indirectly by creating increased roughness along the banks that reduces flow velocities and shear forces.

Temperature can also play a role. Very cold temperatures reduce fish activity and feeding, while warm temperatures can reduce oxygen, impact biological oxygen demand (BOD) and chemical oxygen demand (COD) levels, and instigate fish kills.

7.4.5 Watershed Level Restoration

Many watersheds have had significant levels of logging, road building, and development that affect the volumes and delivery rates of water and sediment to the active channel. Restoration options involved in watershed scale recovery projects can be much more complicated and costly than projects within the river corridor because major changes in land use management may be needed. Where human-induced impacts on the watershed have created landslides, gully erosion, and mass wasting, it may be very difficult to restore hillslope features. Nonetheless, land treatment can have significant benefits to help restore watershed level natural processes. Treatments should be considered that minimize runoff and erosion from flood plains in agricultural areas, minimize bank erosion from grazing practices, and minimize water and sediment delivery as a result of unstable clear-cut or road failure areas along the hillside of the watershed.

As an example, several old logging roads in the Pacific Northwest are used solely as recreational access roads. Inadequate drainage across these roads often leads to hillslope failures and mass wasting. It is difficult to determine the exact quantity of additional sediment and water that is delivered to the river corridor from these hillslope failures. However, in watershed areas such as the Hoh River in Washington, the frequency of hillslope failures in logged areas has increased by nearly 200 percent (Lyon, 2003). The drainage systems that allow runoff to cross under the roads need to be improved through the installation of larger culverts and bridges to minimize the water and sediment delivery as a result of these failure areas. Also, the roads can be decommissioned, modified into foot trails, or hillslope stabilization techniques can be implemented.

7.4.6 Uncertainty and Adaptive Management

Although every restoration project has some degree of uncertainty that success will be achieved, the uncertainty for some projects may be significant. For these projects, an adaptive management program can be implemented to improve the chances for success. Policy agreements between resource managers and landowners should be developed to work with the restoration goals and objectives. Additionally, the adaptive management program should explicitly define how success of the project will be measured. Monitoring, research, and the willingness and ability to take corrective action are other key components to an adaptive management program. The following steps can lead to a successful adaptive management program:

1. Define the restoration goals and objectives and how success will be measured.

2. Formulate a set of hypotheses that explain how a restoration action will achieve a desired result. Even if some or all of the hypotheses are proven false, the information gained will ultimately help the restoration process.

3. Begin implementation of a restoration action, with monitoring designed to test the set of hypotheses. This is different than simply monitoring a list of resource parameters to test for possible trends. When monitoring is designed to test hypotheses, the causes and effects become better understood and at a much faster pace.

4. If the restoration action is not achieving the desired outcome, conduct research to discover why. Monitoring alone may not explain why a hypothesis is false, nor provide insight as to what new or modified management actions may be necessary to achieve the desired outcome.

5. Formulate a new set of hypotheses to explain how a new or modified restoration action will achieve the desired results.

6. Repeat steps 3 through 5 until the restoration success is achieved. An adaptive management program will be successful if resource managers are willing and able to implement corrective actions. Resource managers should not be expected to blindly accept recommendations for new or modified actions. However, objective presentations of study results should help resource managers to make informed decisions.

The actual implementation of an adaptive management program can be difficult if there are significantly different policy views among the many different resource management agencies and interested parties. However, the involvement of all parties is usually necessary for a successful adaptive management program, especially over the long term.

7.5 Summary

The restoration of river channels and flood plains is often complex, and every project has its own unique set of characteristics. River restoration typically requires a multi-disciplinary approach. The ideas presented in this chapter are intended to describe the sediment management aspects of river restoration. The development of a conceptual model of the physical processes and the linkages to biological processes is a good place to start. The conceptual model will help determine the data analysis needs and the feasible range of restoration options. Restoration projects will be most successful over the long term when they are designed to be consistent with natural processes and the concepts of dynamic equilibrium are incorporated. The degree of uncertainty about project performance can be reduced by the implementation of adaptive management, which incorporates monitoring, research, and the willingness to take new management actions.

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