3. Fluvial Processes and Morphology Assessment Methods

A watershed approach toward assessment of fluvial processes and morphology requires utilization of methods that may be put into a framework to both incorporate data collected locally and well as illustrate the processes that link the area under investigation to upstream/upslope and downstream areas within the watershed. Many aspects of fluvial processes and morphology may be measured to help assess a watershed's condition; however, individual measurements are difficult to interpret unless they are placed within the watershed's temporal and spatial context.

3.1 Developing a Watershed Scale Framework for Assessment of Fluvial Processes and Morphology

The goal of developing a watershed scale framework for assessment of fluvial processes and morphology is to develop a coherent process-based, dynamic picture of how everything is connected (or linked), and how processes create and modify morphology within the watershed unit. In their seminal paper "watershed analysis as a framework for implementing ecosystem management," Montgomery et al., (1995) point out that there can be no cookbook approach to watershed analysis because landscapes are inherently variable and simple indices are not always relevant. The CWAM team concurs that there is no single protocol or detailed methodology that can address all aspects of geomorphic processes and morphology within the vast array of complex watersheds throughout California. Nevertheless many good approaches have been developed in order help prioritize and investigate problems in a watershed scale framework. Applied watershed research is a vibrant field of study and new approaches utilize new technology as it develops. Some new approaches and methods are integrated into this chapter, and future updates will necessarily be required as our understanding of watershed processes grows and as results of new science and technology become available.

Chapter Guide

In an effort to understand how fluvial processes are linked to watershed and reach scale morphology, in this chapter we outline initial steps in watershed assessment to aid in focusing the spectrum of potential analyses. This following discussion provides an overview of steps toward developing a watershed scale assessment framework. Details about various methods are described in subsequent sections and in appendices to this chapter or in other noted resources.

> *Document Watershed Boundary, Drainage Network, and Water and Sediment Connectivity.* The drainage network within each watershed is the primary conduit for flow and sediment routing from the headwaters to the mouth. Delineating the watershed boundary and the drainage network within the watershed using maps, photographs and/or GIS yields the big-picture overview of how water and sediment move through a system. Understanding the watershed scale linkages between hillslopes, tributaries, and main channels provides the overall framework for watershed assessments that evaluate changes resulting from human activities and land uses occurring in various portions of the watershed. See CWAM Volume 1, chapter 1 for a description of how to identify watershed boundaries.
>
> *Delineate subwatersheds.* Delineation of subwatersheds allows for focusing on particular questions or problems that need to be addressed while keeping in mind drainage network linkages that may influence or be influenced by activities within the subwatershed. The primary subwatershed delineation should be based on the main tributaries and may be accomplished using maps or GIS mapped hydrographic units (these should be checked). Secondary delineations may be based on similarity of factors such as topography, land uses, vegetation, geology, or soils, or channel slope, valley width, or other characteristics that influence channel processes and morphology. Subwatershed delineation may be useful to identify the relative priority of problems and to focus management efforts within the larger watershed context.
>
> *Reconnaissance.* Reconnaissance provides qualitative information that helps characterize watershed-scale features. Reconnaissance level geomorphic assessment should be conducted at different scales. At the watershed scale, documentation of elements that influence geomorphic processes might include map and photo documentation of features such as: a) lakes, wetlands, or estuaries b) any tectonic, geologic, or structural features that influence hillslope and fluvial processes (e.g. faults, major differences in bedrock lithology etc; c) recognizable flow and sediment transport pathways; d) sediment storage areas (e.g. parts of the watershed that contain floodplains, bars, etc.); and e) human influences. Field reconnaissance at the reach scale is discussed under *Methods to Document Morphology* section in this chapter.
>
> *Identify Dominant Geomorphic Processes and Morphology over Time and Space.* Identification of the dominant geomorphic processes and morphology in various parts of a watershed and how they have changed over time and space helps understand the relevant natural processes and the influence of past and current land uses. At the watershed scale, important processes responsible for creating morphology include hillslope erosion and transport processes, floods, fluvial sediment transport, erosion, deposition, channel migration, avulsion, and tidal

processes in estuarine transitional zones between rivers and the ocean. Critical in understanding how geomorphic processes and morphology change over time and space is identification of pre-historical disturbances and trends (sometimes called the natural disturbance regime) that shaped the landscape in the past, such as those related to climate change, fires, or large landslides and floods, to understand the legacy of past watershed processes and conditions on current conditions. CWAM Volume I, Chapter 3 includes descriptions of some basic geomorphic processes and morphology.

Document Historical Changes and Trends. Document the changes in geomorphic processes and morphology that have occurred during the historical record, such as those resulting from land use activities. This may be accomplished through understanding the dominant processes and morphology and the variability inherent in the natural disturbance regime (as described in the previous task) that provides information necessary to infer how current conditions are influenced by past processes (Montgomery et al., 1995).

Identify Land Uses that Influence Physical Processes. Document infrastructure that acts as a constraint on fluvial processes and land uses such as those that alter flow and sediment supply, transport or deposition. Such elements may include: dams that alter longitudinal transport of water, sediment, and nutrients; levees that isolate floodplains from channels and change sediment transport capacity; structural bank protection or channelized reaches that limit fluvial processes; water diversions that remove flow from the river; grazing that influences riparian vegetation and channel bank erosion; gravel extraction that alters floodplain or river channel topography or bed elevation, etc.

Document Changes in Connectivity. Document and map elements within the watershed that influence connectivity. Some examples include: 1) dams that influence longitudinal connectivity by disrupting sediment transport and flow regimes or by posing migration barriers that prevent in or out-migration of anadromous fish; 2) levees that influence lateral connectivity by disconnecting the channel from its floodplain; 3) sediment or debris basins that trap sediment; or 4) ground water withdrawals that alter interactions between groundwater and river flow.

Identify Cumulative Effects. Addressing the steps outlined above allows for consideration of cumulative watershed effects. Using the knowledge gained through reconnaissance level assessment, identify the relationships between the area of interest and the cumulative effects of multiple land uses over time. A description methods to assess cumulative watershed effects is presented in this volume and in: Reid (1993) http://www.fs.fed.us/psw/rsl/projects/water/reid_141.pdf and in the University of California Committee on Cumulative Watershed Effects (2001) http://nature.berkeley.edu/forestry/curr_proj/cwe/cwe_i.html.

The following sections provide an overview of some of the most common methods used to assess fluvial processes and morphology and discusses why they are important. Each section identifies the types of questions that may be addressed using the method, how to conduct repeatable measurements, considerations of spatial and temporal scale, and ways to interpret the data. Finally, an appendix contains references and links to more detailed descriptions of various methods.

3.2 Methods to Measure Discharge and Sediment Transport

Examples of Questions that can be Answered by Measuring Sediment Transport

- What are the modes of sediment transport (e.g. suspended sediment load, bed material load, total load or turbidity) that need to be measured?
- Where does the sediment filling in the channel come from—the upstream channel bed and banks, or from hillslope sources, or from failing logging roads?
- How much sediment does a river transport during floods of various magnitudes?
- Can the sediment supplied be transported by available flows?
- How do sediment transport processes and rate influence morphology?
- Will gravel mined from the channel be replaced with gravel from upstream without causing incision?
- Will sediment deposition alter morphology, habitat, or cause flooding?
- Will fine sediment eroded from fill behind a dam that is to be removed for restoration cover spawning gravel in downstream reaches?
- Are there alternative methods of estimating potential sediment contributions from a restoration project besides cost-prohibitive field monitoring?

Fluvial processes and morphology result from interactions of water and sediment in watersheds. Quantifying discharge, the volume of water in a river (or river and floodplain) per unit time is necessary in order to put measurements of sediment transport into a watershed context. Discharge is highly variable in natural river systems, and can be placed within a continuum from no or low flow to extremely large floods—each having an important role to play in watershed dynamics and ecology. Discharge and its relation to other components of river ecology (e.g. sediment, fish, etc) is a fundamental component of river management and restoration. Whereas low magnitude flows are critical to survival of aquatic biota, relatively high magnitude “flushing” flows” are needed to mobilize and keep coarse sediment from being clogged with fine silt and clay and “overbank” flows are required to create and sustain floodplain structure. Appendix I, describes some general methods for determining discharge when there is no gaging station present.

Understanding sediment transport requires substantial knowledge—and measuring sediment transport requires substantial dedication. Measuring sediment transport is tricky because of the inherent temporal and spatial variability of sediment transport processes—especially in California, where rainfall and streamflow is seasonal and episodic. Thus, the value of short term sediment monitoring is often questionable—especially during dry years when sediment transporting flows are infrequent. Hicks and Gomez (2003) stress the importance of three steps in developing a sediment transport monitoring program: 1) define the purpose of the measurements; 2) determine the measurement approach; and 3) determine the appropriate tools to use in measuring sediment transport. Sediment transport problems can address supply, storage, and yield – or the elements of a sediment budget; routing—or the pathways sediment follows from the headwaters to the mouth of a watershed; total sediment load, bedload, suspended load, and turbidity. Each type of problem requires a different approach and set of tools to help understand the problem, and sometimes even using a combination of tools and data collection methods over the long term leaves us with many uncertainties. At the same time, long-term analysis of sediment transport in fluvial systems is critically important because it is one process responsible for creating and maintaining morphology and that influences water quality.

Coarse bed material transport is responsible for creating and altering channel morphology, in contrast to fine sediment such as silt and clay that are transported through the system more rapidly. Thus, the following section begins with a description of the important concept of flow strength and the threshold of entrainment required to mobilize the coarser material as an introduction to the type of measurements needed to assess the processes responsible for creating morphology. Appendix II provides some resources that illustrate methods of measurement of sediment transport.

Flow Strength and Threshold of Entrainment

In order for sediment transport to occur in gravel bed channels, flow strength must exceed a critical threshold, called the critical threshold of entrainment, or threshold of mobility. Flow over the surface of a channel and floodplain creates a boundary shear stress field. As discharge increases, shear stress increases above a threshold and starts the process of sediment transport. A comparison of the flow strength available during a given discharge to the critical shear strength needed to mobilize the sediment on the bed of the channel helps us predict whether or not sediment transport is likely to occur, and to some degree, the sediment size likely to move. Although sediment transport in natural rivers is wildly variable, relatively simple approximations based on simple flume experiments are commonly used to predict transport. From laboratory flume experiments using homogeneous spherical grains the Shields criterion may be calculated as:

$$\theta = \tau_c^* = \tau_c / (\rho_s - \rho) g D$$

where:

θ or τ_c^* is the Shields Criterion, a dimensionless value of shear stress at the critical condition (e.g. at the threshold of entrainment)
τ_c is boundary shear stress at the threshold of entrainment;
ρ_s is sediment density and ρ is water density;
g is gravitational acceleration;
D is grain diameter, usually D_{50}

Although sediment transport is really more complicated in rivers where there is turbulence, bed and bank irregularities, and vegetation, the Shields criterion equation is useful because in order to calculate the critical shear stress, τ_c, the only data needed includes $D_{50,}$ the median grain size measured and laboratory defined constants for ρ_s, ρ, and g. In the field, the critical shear stress can be determined as the shear stress measured at the onset of bed material transport using the equation for boundary shear stress: $\tau_o = \rho g R S$ where R = hydraulic radius ~depth, and S = slope. The flow depth may be derived from discharge measurements, whereas slope is calculated from field data collected at the reach scale, described in subsequent sections. Values of τ_c^* for coarse sediment usually range from 0.03 to 0.06 and a value of 0.045 is common. A summary discussion of the Shields Criterion, and its determination and limitations can be found in Knighton (1998) or Richards (2004).

The threshold of particle motion may be evaluated using other measures of flow strength besides critical shear stress τ_c, including critical stream power per unit bed area, ω_c, or critical velocity, v_c. The threshold of critical stream power, important in floodplain classification is described below. A discussion of the velocity threshold, defined by Hjulstrom in 1935 may be found in Knighton (1998), Mount (1995), or Richards (2004).

Stream power per unit bed area,ω, often called the “unit stream power” is:

$$\omega = \gamma QS/w$$

where: γ = unit weight of water (ρg); Q = discharge; S = slope; and w = channel width. The threshold of critical power, ω_c, is the stream power needed to transport sediment, whereas available power, ω_a, is the actual stream power at the instance measured. The threshold is defined as the point when $\omega_a / \omega_c = 1$. Sediment transport occurs when $\omega_a / \omega_c > 1$, and no transport occurs when $\omega_a / \omega_c < 1$. Stream power per unit bed area may be calculated using discharge measured as described above, and slope and width as part of reach scale field measurements as described below.

Limitations of simple one-dimensional uniform flow equations such as those described here are significant; however headway toward practical applications for more sophisticated approaches is being made in an energetic field of study. For example, a review of the theory behind sediment transport is provided on-line in “Transport of Gravel and Sediment Mixtures” by Gary Parker http://www.ce.umn.edu/~parker/manual_54.htm and in numerous textbooks. Lecture notes, analytical spreadsheets, and relevant papers by Peter Wilcock—from a sediment transport seminar held January 26-28, 2004 at UC Berkeley—are available at http://socrates.berkeley.edu/~geomorph/wilcock/wilcock.html.

Spatial and Temporal Scale of Sediment Transport Measurements

Sediment transport problems may be investigated at a variety of scales, from the particle scale, where entrainment and the threshold of mobility are important—to sediment routing, where the pathways sediment takes as it moves from hillslopes to tributaries and channels downstream toward the watershed outlet. Moreover, often reach scale sediment transport is important—if we want to understand the relations between sediment supply, erosion, and deposition and how that affects habitat. The sediment budget framework described in CWAM Chapter 3 is useful as a tool to organize sediment transport measurements that may take many years to assemble. Long-term data collection is necessary in order to distinguish between normal variation and longer term trends because of the episodic nature of sediment transport in California.

What do Individual Sediment Transport Measurements Mean?

Sediment transport measurements yield a variety of data including parameters such as suspended sediment concentration, load, or grain size distribution, turbidity, bed material load, size distribution, and transport capacity. A detailed review of individual measurements and how to analyze and interpret data is provided in Hicks and Gomez (2003).

Appropriate Use of Sediment Transport Data/Limitations

Sediment transport measurements conducted in the field generally contain a huge amount of scatter because of the natural variability inherent in fluvial systems. For this reason, monitoring sediment transport over relatively long time frames is needed to improve confidence that measurements are representative of a watershed's sediment transport regime.

Inadequate funding of projects often limits the usefulness of monitoring data collected—and a hard look at the usefulness of data collected for any particular project over a relatively short timeframe should be undertaken prior to collecting a year or two of data. Sediment monitoring prescriptions based on satisfying policy or regulations should be avoided in favor of monitoring based on understanding physical processes. For example, monitoring for a three-year period after project completion may never actually document sediment transport if no storms occur during that period. Additionally, baseline monitoring in a river upstream and downstream of a small project is unlikely to show statically valid changes. Care should be taken to facilitate sediment monitoring so that it provides useful information suited to the uniqueness of any project. If time and funding are inadequate within a project to allow for geomorphically appropriate data collection—alternative approaches to evaluate project effects should be considered.

There are many limitations related to using Shields criterion for determining particle mobility, e.g. bed material is heterogeneous, not spherical sand grains assumed in the relation; the relation neglects turbulence and lift forces; and the relation excludes sediment characteristics besides grain diameter that may be important in entrainment, such as packing, or degree of exposure vs. hiding of individual grains. The Shields criterion has been modified by numerous researchers that evaluated the range of values for different types of rivers.

The large amount of scatter in transport measurements arise as a result of many factors, with bedload, rating curve relations are affected by: sediment supply, channel geometry, bed material distribution. Bedload or suspended load rating curves are empirical relationships---and measurements over a wide range from small to large floods that transport sediment are needed. Suspended sediment transport is subject to "hysteresis" where more sediment is supplied and transported during the rising stage of a hydrograph, or during the first few storms of a season—than on the falling stage of the hydrograph or during later storms. Therefore, development of relationships between suspended sediment, turbidity or bed material load and discharge, or rating curves, requires a substantial effort that includes measurements throughout individual storms, throughout entire seasons, and over many years. However difficult these data are to obtain, these relationships are still needed to calibrate sediment transport models and initiating a long-term sediment monitoring program is useful. Such long term data collection efforts help identify changes in the relationship over time and allow for assessment of watershed trends and responses to various land use changes. When possible, using measurements in conjunction with models provide the most information. However, models based on short-term data collected (especially if few or no high flows occurred during that time) can lead to significant error. Thus, the purpose of a model becomes important—if the purpose is to explore the influence of various changes in sediment supply, channel shape, or other land use changes on processes—such preliminary data may be informative. However, if the model is intended for any type of regulatory purpose that requires quantification of loads, for example, a longer term data set representing a fuller range of flow conditions is needed. Examples of sediment monitoring efforts that are geomorphically effective include long-term programs such as those carried out at Caspar Creek (USFS) and Redwood Creek (NPS).

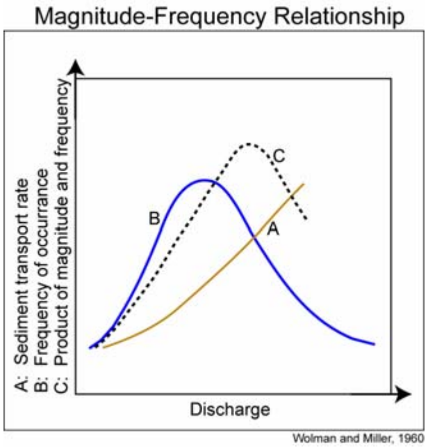
3.3 Methods to Calculate Effective Discharge

Examples of Questions that Can be Answered by Calculating Effective Discharge

- What is the range of dominant or effective discharge that creates and maintains channel shape and size?
- What size should a "natural" of self-sustaining restored channel be given the current sediment and discharge regime?
- What is the difference between the dominant discharge range and the range of discharges currently released from a dam?
- What discharge must be released from a dam in order to flush fine sediment from the gravel framework?
- What range of flows is responsible for the majority of sediment transport over time?
- Is the dominant discharge a useful design parameter in restoration?
- Is the dominant discharge the same as the morphologic bankfull? Has incision occurred?

"Effective" discharge refers to the range of flow magnitudes that transports the majority of a river's annual sediment load over the long-term (Wolman and Miller, 1960). In a gravel bed stream, this is the discharge that transports the greatest quantity of bedload. The "dominant discharge" concept refers to the flow magnitude that determines channel shape, or cross section width and depth (Wolman and Leopold, 1957). Realistically, there is a range of flows responsible for creating channel form, rather than one single flow magnitude. The calculation of the range of discharges responsible for forming and maintaining channel form requires information on both flow discharge and sediment transport. The magnitude-frequency relationship, an important concept that these methods are built upon is discussed in CWAM section 2.2.

A method developed by Wolman and Miller (1960) illustrates the dominant or effective discharge as the maximum of the product of flow frequency and sediment transport rate. There are three steps to calculating the range of the dominant discharge: 1) Develop a sediment rating curve, A; 2) develop a plot showing the frequency of flows of various magnitude discharges, curve B; and 3) form a third curve that is the product of the flow frequency and sediment rating curve, C. The combination of the frequency of occurrence of flows and sediment transport curve illustrates that the flow that does the most geomorphic work, e.g. dominant or effective discharge, is at the point on the graph where the product of frequency of flows and sediment transport is at a maximum. This is the channel forming flow. Sometimes the dominant or effective discharge is equivalent to bankfull flow, but not always.



In reconnaissance level studies, dominant discharge is usually assumed to be the flow represented by some relatively frequent flood recurrence interval, e.g. the 1- to 3-year flood; however this estimate should be verified by data collection and analysis (FISRWG, 1998). In any case, a range of magnitudes should be considered rather than one average value. Methods to accomplish this analysis are included in Appendix III.

Methods for Determining "Bankfull" Discharge

"Bankfull" discharge is the flow magnitude that is contained within a channel without overtopping its bank (Leopold et al., 1964). Leopold et al. (1964) found that this flow was significant in creating the shape and size of alluvial channels—the channel forming flow, and that on average, this flow had a recurrence interval of about 1.5 years. The term sometimes leads to confusion, as there are two ways used to define bankfull, using: 1) morphologic indicators; or 2) flow recurrence interval.

Morphologically, bankfull refers to the flow that fills the channel from the top of bank on one side of the stream to the top of bank on the opposite side. Morphologic bankfull is easiest to recognize in the field when a floodplain is present adjacent to the channel; the point discriminating where water is contained in the channel and where it begins to spread out onto the floodplain is designated as bankfull. However, when there is no floodplain present, or when the floodplain elevation relative to the channel is inconsistent, other indicators are used to denote the relatively frequent channel forming flow. Such indicators include the lowest elevation of tree roots exposed on the channel bank, small benches or morphologic breaks in slope along the channel bank, debris lines from frequent floods, changes in particle size from coarse gravel and sand to silt and clay; or perennial vegetation, etc. Bankfull is generally the point where the width to depth ratio is at a minimum (Wolman, 1955). Field determination of the bankfull discharge is described by Luna B. Leopold for western streams and M. Gordon Wolman for eastern streams in a video: http://stream.fs.fed.us/publications/videos.html. It is important to note that the morphologic indicators may not agree with the area of channel containing a flow with 1.5 year recurrence interval, especially if the channel is incised. Using a combination of methods and defining the indicators is essential so that assessment results area easily interpreted during subsequent years. Thus, it is important to define if bankfull was determined by morphologic or recurrence interval methods.

Spatial and Temporal Scale for Evaluating Effective Discharge

Effective discharge is usually calculated where gaging station data are available, such as at USGS gaging stations. If discharge and sediment transport data area available for a gaging station, estimating the effective discharge is relatively straightforward. The accuracy of such estimates increase with the length of record available. Estimating flow recurrence intervals as an indicator of bankfull flow or dominant discharge is also accomplished at gaging stations, whereas morphologic determination of bankfull is conducted in the field, at the reach scale.

What Individual Measurements of Effective Discharge Mean and Appropriate Use of Data/Limitations

Methods to estimate effective discharge are subject to the measurement error and uncertainty in estimating sediment transport rating curves and discharge frequency curves. In channels that are incised, the morphologic indicators of bankfull may greatly exceed the channel forming flow and in most of California's rivers, the top of bank, or morphologic bankfull, may not be an appropriate proxy for channel forming flow. Moreover, it is likely that a range of flow magnitudes, not a single flow discharge with a recurrence interval of 1.5 years, is responsible for the shape and size of the channel. In some alluvial rivers, the dominant, bankfull, and effective discharge are equivalent, and generally correspond to frequently occurring flow magnitudes. However, this assumption is not valid in all rivers, for example in disturbed channels or rivers in semi-arid or arid environments.

Estimates of effective discharge may be used to help ascertain the flow necessary to sustain channel form and process or to estimate stable channel size. One channel design approach sometimes used in restoration projects utilizes estimates of effective discharge to estimate stable channel dimensions—using "hydraulic geometry relationships," (Leopold and Maddock, 1953; Leopold et al., 1964) or regime equations (reviewed in Hey, 1997). However, these methods rely on identification of a reference reach or measurements of some system deemed to be stable enough use as a desirable model for restoration of disturbed systems—and in California, undisturbed reference reaches are quite rare, if they exist anywhere. While enticingly simple, approaches that design uniform widths and depths based on quasi-empirical data developed for another watershed or another region may neglect the unique characteristics of the particular watershed under investigation.

3.4 Methods to Assess Substrate and Grain Size Distributions

Examples of Questions that can be Answered by Assessing Substrate and Grain Size Distributions

- Is the reach a boulder-bed channel consistent with step-pool morphology or a gravel-bed channel consistent with riffle-pool sequences?

- What magnitude flow is required to mobilize sediment in this reach?
- What is the ratio of coarse to fine sediment in riffles and pools?
- Is the fine sediment content excessive?
- Is the size distribution of sediment substrate favorable for spawning habitat?
- Has the size distribution changed over the past decade due to a particular upstream land use?
- Has pool depth changed over the past decade due to an influx of fine sediment that is stored in pools?
- Are channel bed and banks composed of natural material, or materials that alter their roughness—and in turn the flow velocity (e.g. rip-rap, or concrete).

Summary of Methods to Assess Substrate Grain Size Distribution

The character of sediment on the bed of a river channel or floodplain influences sediment transport and is an important component of aquatic and aquatic-terrestrial ecotone habitat. Measurement of sediment substrate helps us understand local conditions, as well as the influence of upslope and upstream inputs. Monitoring various substrate parameters may be used to document changes in sediment sources, supply, and transport regimes. Particle or grain size is the most common parameter investigated in watershed assessments. Such measurements are necessary for sediment transport models, and assessment of habitat.

Sediment substrate may be highly variable both in space and time, existing in patches that reflect local sediment transport and deposition conditions, or changing in response to individual floods. Prior to embarking on a sampling program, it is essential to define the question the data is intended to answer, to develop a sampling strategy that addresses the specific question. A comprehensive description of sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams is provided in the following general technical report (Bunte and Abt, 2001) http://www.fs.fed.us/rm/pubs/rmrs_gtr74.html. Geomorphic principles behind development of a sampling strategy and analysis methods are provided in resources such as Kondolf et al (2003). Kondolf (2003) also reviews appropriate scale for assessments, methods and analyses, limitations of various methods, and strategies for interpreting data related to issues such as spawning gravel quality. Discussion of the sample size needed to represent grain size distributions are described in Church et al., (1987).

Description of Methods to Assess Substrate and Grain Size Distributions

Numerous methods for analysis of sediment size distributions have been employed in attempts to characterize the variability of sediment present in river systems. Methods range from analysis of photographs showing substrate to freeze cores Bunte and Abt (2001). Appendix III describes the steps in conducting a “pebble count,” or an analysis of coarse surface sediment through random sampling of grains in a particular area (Wolman, 1954). The method requires setting up a sampling grid or series of lines that the practitioner walks along. The sampling area could include defined features such as: a bar, riffle, or pool or across a combination of individual features. Despite the limitations of this method, it provides a relatively simple way to characterize bed material in rivers with coarse bed material. A summary of limitations of the pebble count and alternative methods to document surface sediment size distributions are provided in Kondolf et al. (2003).

In some cases, it is more appropriate to measure subsurface sediment than surface sediment—for example when one wants to estimate the size distribution of material that the stream typically carries. Methods to collect bulk subsurface sediment samples are also provided in Church, et al., (1987); Kondolf et al. (2003); and on-line in Lisle and Eads (1991): http://www.fs.fed.us/psw/publications/lisle/Lisle91.pdf.

V* a Measure of Excess Fine Sediment in Pools

Hilton and Lisle (1993) provide a method for measuring the fraction of pool volume filled with fine sediment http://www.fs.fed.us/psw/publications/documents/rn-414/rn-414.pdf. This fraction, called V*, is defined as the ratio of fine sediment volume to pool water volume plus fine sediment volume. V* may be a useful indicator of the character of sediment supply in monitoring programs. Estimates of V* in 10-20 pools are needed to characterize variability between pools within a reach. Repetitive measurements of V* within the same pools over time can help identify long term trends. The geomorphic principles behind the V* measurement and a discussion of its application and limitations is provided in Kondolf et al. (2003).

3.5 Methods to Assess Morphology

Examples of Questions that can be Answered Through Measuring Morphology

- What is the dominant bedform type in various reaches of the channel?
- What is the relation between large woody debris and bedforms in the channel?
- What is the relation between cannels and floodplains in this system?
- What is the slope of the channel?
- What is the width to depth ratio of the channel, and has it changed over time?
- What types of bedforms contain coarse sediment and what types contain fine sediment?
- Has sinuosity changed over time?
- Where and how much bank erosion is occurring? Is it related to natural channel migration processes or to land use disturbances?

Fluvial morphology results from dynamic interactions between water and sediment over the range of flows that transport, erode, and deposit sediment within a watershed. Moreover, the morphology influences flows in a way that alters these same fluvial processes depending on such factors as sediment supply, vegetation, and human activities. The relation between the processes that create and alter landforms and the resulting morphology is complex and varies over time and space. Assessing morphology requires linking form to process in order to understand changes and apparent trends. Thorough descriptions of the linkage between processes and morphology are provided in many classic (e.g. Leopold et al., 1964) and recent text books including, Knighton (1998), Wohl (2000), Bridge (2003), Richards (1982; 2004), and Brierley and Fryirs (2005). A discussion of river change and the length of time and pathways followed for a river to recover after disturbance are provided in Knighton (1998). Mount (1995) provides examples of the influence of various land uses in California on river processes and morphology. Simon and Castro (2003) review the notion of “stability” in a quantitative framework that addresses the balance or imbalance between the applied forces and the boundary resistance. One common method for addressing morphology is the classification of morphologic features (discussed in Appendix VI). The relation between form and process is at the heart of assessing river morphology discussed in the following sections.

Fluvial Processes and Morphology at the Reach Scale

Assessment of fluvial processes and morphology and documentation of changes over time are often conducted at the scale of a “reach”. The first question to ask is: how long should a reach be? The answer depends on the question being asked and the physical characteristics of the channel itself. Selecting a channel reach length of about 10 to 20 times the average channel width (Leopold et al., 1964) is commonly used—others have suggested reach lengths of at least 6-30 times the channel width and including two complete riffle-pool sequences (Simon and Castro, 2003). Assessment of morphology at the reach scale is intended to document some of the variability inherent in natural systems, and helps ascertain fluvial characteristics that are representative of that section of the river—so definition of a reach depends on the particular river being considered. For example, in order to characterize a meandering river, a reach might need to be longer than 10 or 20 times the channel width so that the reach encompasses complete meander wavelengths—instead of truncating them mid way—and with enough up- and downstream length to provide context for the areas of interest. In other words, it is important to look outside of the channel banks. In contrast to the reach scale that may include multiple cross sections, data from a single cross section, say over the deepest part of one pool, or across one riffle, lacks the context to understand the natural variation inherent in rivers.

Methods to Measure Planform

Reach scale assessment can address planform changes (e.g. meander migration or avulsion) that can be identified on maps or from aerial photographs or other spectral images. Assessment of planform from various images can document the relation between channels and floodplains, and if the channel is straight, meandering, braided, or anabranching—or some combination of these endpoints of the continuum of channel patterns. Methods employed to characterize planform include documentation of whether the system is a multiple channel system or a single channel system and determination of sinuosity, migration rate, and floodplain drainage density. Many rivers today are confined into single channels, whereas, prior to human activities and land use changes they were multiple channel systems where the floodplain was an integral component of the system. Investigations that compare historical to current maps or photographs are invaluable in inferring dominant processes prior to human activities and documenting changes. Some important parameters to measure planform include:

Sinuosity

Sinuosity (s) is a measure used to quantify the difference between meandering and straight channels. Sinuosity of a channel is defined as the channel length (L) measured along the center of the channel divided by the valley length (L_v) measured along the valley axis (Schumm, 1963):

$$s = L/L_v$$

Sinuosity of natural rivers generally varies between 1.0 (straight channels) and 3.0 (highly sinuous, or "tortuous" meanders).

Migration Rate

The migration rate is a measure of how quickly a meandering channel erodes through floodplain sediment on the outside of a bend while maintaining a relatively constant channel width--and is defined as the distance a channel moves divided by the time it takes. However, over a certain length of channel, such as around the outside of a meander bend or a longer reach, the rate of migration is variable, with some portions eroding faster than others. Thus, the migration distance is often averaged by measuring the area (A) that is eroded by the migrating river divided by the length of channel considered (L). The migration rate here given as the variable (M_r), is determined by dividing the ratio (A/L) by the time period of measurement (t):

$$M_r = (A/L)/t$$

Number of channels and Floodplain Drainage Density

The interrelation between channels and the floodplain in multiple channel systems can be quantified using morphometric parameters that characterize the anabranching system attributes: 1) the number of channel segments ()*n*; 2) the length of channel segments (*L*); and 3) floodplain drainage density (*D*):

$$D = \Sigma L/A$$

where ΣL is the sum of the lengths of all channel segments within a measured floodplain area, *A*. In particular, floodplain drainage density is a useful parameter used in this context to quantify changes in channel-floodplain interactions in lowland river systems where channel floodplain connectivity sustains floodplain ecology (Florsheim and Mount, 2003).

Topographic/bathymetric maps require three dimensional data that may be gained through LIDAR, SAR, AVARIS, LANDSAT or other spectral imagery. The National Science Foundation supported Center for Airborne Laser Mapping (NCALM) provides high resolution mapping of topography that could revolutionize our ability to interpret hillslope and fluvial processes when it becomes more widely available (see http://www.ncalm.ufl.edu/ for an example). Data from the Shuttle Radar Topography Mission: http://srtm.usgs.gov/srtmimagegallery/index.html already provides publicly accessible images of various locations in California. A summary of methods that utilize various types of data to assess historical conditions is provided in OWAM Chapter 2 http://www.oregon.gov/OWEB/docs/pubs/wa_manual99/02_history_print.pdf.

Field Reconnaissance

In field reconnaissance at the reach scale, specific observations are recorded in order to provide a representative description of channel morphology. Reconnaissance at the reach scale can include elements such as whether the channel is bedrock or alluvial, where there is a floodplain, riparian vegetation, bank erosion, and large woody debris, and channel profile, slope, the type and character of bedforms and bars, cross section width and depth, bed material character, and roughness. Detailed guidelines and a series of worksheets to record data collected during a stream reconnaissance are provided in: Thorne, C.R. (1998). Documenting locations of the reconnaissance observations on map, and keeping detailed notes and photos describing the location aid in using reconnaissance level observations as the basis of assessing changes over time.

Reach Scale Geomorphic Maps

Constructing a reach scale geomorphic map provides an illustration of how morphologic or ecologic data fits together in the context of other field measurements, including profiles, cross sections or other points surveyed or sampled. Mapping may be accomplished in two dimensions as an overlay to maps or spectral images described above, or in the field using a measuring tape and Brunton compass by plotting angles between measured distances or in three dimensions using data measured using an electronic distance meter (EDM), field based LIDAR, or other survey instruments. Such geomorphic maps document the spatial relationships between physical and sometimes biological components of a reach, and are useful as a base map to record locations of bank erosion, large woody debris, channel bars, bedforms, the edge of water in the channel at the time the map is constructed, etc. Maps prepared from EDM data provide three dimensional views of channel, floodplain and estuarine morphology.

The measured distances between cross sections along the longitudinal profile and compass bearings along the cross section lines are useful data to aide in constructing a geomorphic map of the study reach using a protractor ruler. Plotting these data creates a template upon which other characteristics may be added. Such details are measured using a tape or rangefinder and compass, GPS, or sketched in to illustrate locations and dimensions of riffles, pools, large woody debris, overhanging banks, bedrock protrusions, riparian vegetation, or other attributes of the channel morphology and ecology. The locations of other samples collected or measurements made within the study reach, including bed material size measurements should be recorded on the map so that future measurements are in the same location and can be compared to the baseline data. Geomorphic maps are useful tools in long-term monitoring programs where changes such as bank erosion, or addition of large woody debris may be documented. Harrelson et al., (1994): http://stream.fs.fed.us/publications/PDFs/RM245E.PDF further describes procedures for establishing permanent channel reference sites including selecting and mapping a site.

Survey Level Documentation: Methods and Benchmarks

The morphology of a river may be documented by surveying topography, cross sections, and profiles, usually at the reach scale. Topographic surveying requires use of laser or electromagnetic levels, while profiles and cross sections may be surveyed using these same instruments, simpler automatic levels, or even hand levels. The purpose of surveying longitudinal profiles and cross sections of a channel and floodplain system as part of a watershed assessment is to document and characterize morphology in a quantitative and repeatable manner. The data collected are tied to a permanent datum (arbitrary or absolute) and to permanent starting and ending points. These techniques provide data needed to characterize the physical characteristics of a reach and may become the basis of assessing changes over the long-term. Geomorphic data are then analyzed to provide variables such as slope, width, depth, and hydraulic radius needed along with median particle size to calculate fluvial parameters that help relate changes in morphology to fluvial processes, e.g. critical shear stress needed to entrain sediment, etc. Details of profile, cross section, and topographic survey methods are included in Appendix IV.

Methods for Measuring Erosion and Deposition

Erosion is a natural process where running water removes sediment from the channel bed or banks. Erosion, or scour occurs when the boundary shear stress available is greater than the critical shear stress needed to mobilize and transport the sediment ($\tau_o > \tau_c$) and the sediment mobilized and transported from an area is not replaced by sediment transported from upstream. Deposition is the laying down of sediment by running water that occurs when the boundary shear stress created by the flow is less than that needed to transport sediment ($\tau_o < \tau_c$), a condition that commonly occurs during the receding limb of the hydrograph when flow transporting bedload loses its ability to move sediment grains. Sediment deposition and erosion that takes place episodically during flows capable of initiating sediment transport are both essential processes for creating and maintaining channel morphology. This section describes methods for measuring bank erosion, and bed erosion and deposition (scour and fill) in a channel or on a floodplain.

Bank erosion

As described in CWAM Chapter 3, bank erosion is a natural process that occurs due to the force of water against the bank. Identifying whether bank erosion is part of a river's attempt to maintain a relatively constant width during channel migration or if the river banks are eroding because of riparian vegetation removal and a decrease in bank stability, or some other human activity is important to understanding the issue. In channel migration, or meandering, sediment supplied from upstream is deposited on a point par on the inside of the bend while sediment eroded from the outside of the bed is transported downstream. In contrast, when stabilizing root systems are lost, the channel can widen and in turn alter flow and sediment transport processes.

In reconnaissance level assessment at the scale of a reach, bank erosion may be documented by noting the type of erosion or bank failure, the character or absence of riparian vegetation, the extent of any riparian buffer, or nearby erosion control structures that may deflect flow toward the channel bank or generate turbulence around hard edges of the structure.

Field methods to measure bed erosion include comparison of data such as cross sections surveyed before and after some time period or by using a marker such as an erosion pin. The rate of bank erosion may be documented by comparing cross sections surveyed in the same permanently monumented location over time, where the rate of bank erosion is equal to the change in width divided by the length of time between the two measurements. In order to initiate a long-term monitoring program that addresses bank erosion, the monumented cross section endpoints must be set far enough back from the top of the channel bank so that when erosion occurs, the cross section endpoint remains stable. An "erosion pin," or bolt and washer— is constructed as a bolt driven into the bank with a washer flush with the bank surface that marks the initial contact point. As erosion occurs, the space between the washer and the bank surface will increase. An array of erosion pins may be installed to quantify small rates of erosion that are difficult to document using cross section surveys (since the erosion distance may be less than the diameter of the survey rod).

Bank erosion is episodic, and long-term measurements are needed to assess the interactions between fluvial processes, land uses, bank erosion, and channel morphology. Several methods to analyze changes in channel width and to predict future bank erosion are reviewed in Simon and Castro (2003).

Scour and Fill

During floods, the channel bed may increase and decrease in elevation as a result of the variation in sediment supply and transport capacity natural in dynamic watersheds. Erosion of sediment, sometimes termed "scour" or "degradation" and deposition of sediment, sometimes termed "fill" or "aggradation," occurs at various magnitudes during individual floods. Over the long-term, this variation in erosion and deposition may essentially balance over time—yielding a stable channel elevation, or a trend toward either scour of fill.

Repetitive cross sections or topographic data may be compared to quantify the magnitude and rates of elevation changes that represent changes in sediment scour or fill quantities and patterns over time. Lisle and Eads (1991) note that cross sections only represent the net bed elevation change, while the actual change during an event may be higher. This has implications for questions related to the influence of floods on salmon redds. Placement of "scour chains" aid in documenting the short-term maximum scour during individual events, as described in: http://www.fs.fed.us/psw/publications/lisle/Lisle91.pdf.

Spatial and Temporal Scale of Morphology

Geomorphic investigations focus on understanding the processes responsible for creating the morphology, and collecting field data often requires some iteration in order to adapt to the peculiarities of the fluvial system at hand and to provide data that answers the questions being asked. A fundamental requirement of geomorphic assessment is that the spatial scale of the assessment area encompasses the scale of possible morphologic responses to the range of magnitudes of fluvial processes. For example, assessment of morphology related to anadromous fish habitat must include documentation of all of the components of the fluvial system that these fish use during their life cycle, including channel bedform, substrate, and bank characteristics, floodplain-channel connectivity, and the relation between fluvial processes and morphology during a range of flows from summer low flow to high magnitude winter floods. Reconnaissance level assessment is useful to help structure a more detailed reach level measurement strategy that provides the information needed. Initial baseline surveys to describe existing conditions are needed as a standard to compare to future measurements repeated in the same location. Understanding the range of variability of natural processes, and assessment of long-term trends and change requires a commitment to long-term monitoring. The hierarchy of geomorphic scales is described the description of classification methods in Appendix VI.

Appropriate Use of Morphologic Data/Limitations

Fluvial systems are highly variable in time and space, and assessment of processes and morphology is a rigorous undertaking. For example, one single cross section measurement may only tell us about conditions only at that one instant in time, whereas a series of measurements at the same site over many seasons could tell us about trends and how a channel responds to watershed changes through time. Similarly, an individual cross section may tell us about aquatic habitat at one location, such as in one pool or riffle, whereas a set of measurements extending over many riffle-pool sequences (e.g. through a “reach” of channel) or a detailed topographic channel-floodplain map may give us a fuller sense of how watershed changes influence the physical component of aquatic conditions. Moreover, a set of measurements throughout a reach (or several reaches) can help us understand differences upstream or downstream of a particular tributary or land use disturbance. Finally, short-term monitoring of monumented sites may provide useful data to help understand variation over the particular time period measured---but the limitations of extrapolating such data to understand how processes affect the long-term response of the system should be clearly stated.

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APPENDIX I. Methods to Measure Discharge

Methods to Calculate Discharge from Measurements

Discharge is calculated as the product of flow velocity and cross sectional area, thus, measuring discharge requires information on both flow velocity and the channel or channel and floodplain area inundated by particular flows. Methods to measure discharge are based on the continuity equation that relates the velocity of flow at a cross sectional area of a channel or floodplain. The continuity equation relates flow discharge, Q (in units of m^3/s, ft^3/s, liters/s, gal/day, etc) to other flow and channel parameters:

$$Q = Av = w\ d\ v$$

Where:

Area, A (m^2, ft^2)
Velocity, v (m/s, ft/s)
Width, w (m, ft)
Depth, d (m, ft)

Measuring discharge requires time. It is often desirable to build a “rating curve,” a relation between discharge and stage so that during a storm, one can quickly read a staff gage instead of measuring discharge. However, a rating curve is an empirical relationship---that means that in order to develop a rating curve, we first need to take the time to measure discharge over a range from low to high magnitude flows. It may take several years or longer to develop a rating curve that includes high flows, but only using low flow measurements to develop a rating curve is misleading. For example, over the time period that rating curves are developed, one high magnitude flow may alter the stage-discharge relationship, indicating the sensitivity of the relationship to relatively infrequent higher magnitude floods.

There are numerous ways to measure velocity, from very simple methods that provide a coarse level of detail, to very detailed measurements using sophisticated equipment that provide a finer level of detail. The following describes: 1) a range of equipment available to measure velocity; 2) the protocol for measurements required to calculate discharge using the continuity equation. A review of several methods is included in Whiting (2003). Additionally, many methods to measure water discharge are outlined by the USGS in http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/QMeas.tmp/index.htm and http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/QMeas.tmp/index2.htm

Equipment Available to Measure Velocity

Float, Tape, and Timer. A float is a piece of wood or other buoyant object that is placed in the flow to estimate average surface velocity in one dimension, usually in the longitudinal direction. The method is appropriate in situations where only an approximate estimate of velocity is needed, or when flows are too large to wade across the channel safely.

Propeller (1-dimensional [1-d]; e.g. Price AA or Pygmy meters). A propeller meter consists of a small metal propeller placed in the flow, where the propeller is rotated by the flowing water. The number of revolutions of the meter per unit time correlates with flow velocity. A current meter is attached to the end of a rod that may be hand held by someone wading, or extended over a bridge, from a boat, or from a cableway.

Electromagnetic (1-d; e.g. Marsh McBirney). Electromagnetic meters rely on the voltage produced when water (a conductor) flows through a magnetic field produced by the probe. The measured voltage is linearly proportional to flow velocity. Electromagnetic meters may also be attached to the end of a rod that may be hand held by someone wading, or extended over a bridge, from a boat, or from a cableway.

*Hydroacoustic Current Meters: Acoustic Doppler Velocimeter (3-dimensional [3-d]; ADV); Acoustic Doppler Velocity Profiler (3-d; ADCP; Boogie Dopp). H*ydroacoustic current meters rely on acoustic energy reflected by bubbles and by suspended sediment. In an ADV, receivers measure the velocity differential between the scattering objects at a single point, whereas in an ADCP, velocity is measured at multiple points. Receivers around probe head measure a Doppler shift resulting from velocity differential between the scattering objects. These meters can measure velocity in three-dimensions, and thus can measure 3-d turbulent variations.

Laser Doppler Velocimeter (1 to 3-d; LDV). Laser Doppler Velocimeters use laser light scattered by small particles moving through a volume of water sampled. Light is scattered at a frequencies related to velocity components, and measure the Doppler shift.

Measurements Needed to Calculate Discharge

Once average channel velocity is measured along a cross section, discharge may be calculated in the manner describe below, or with the aid of structures placed in the channel such as using flumes, weirs, or tracers. The following section describes measurements to calculate average channel velocity using the equipment described above. Further methods to determine discharge are reviewed in many resources such as: Whiting, (2003) and in many other resources such as the USGS guide: How to Measure Water Discharge: http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/QMeas.tmp/index.htm.

Discharge Calculation using Current Meters

Propeller or electromagnetic current meters used in wadable streams or suspended from bridges or boats generally use an incremental method that divide the cross sectional width into smaller increments on the order of about 0.5 m depending on the channel width. Flow velocity and depth are measured at a width corresponding to the mid-point of each increment, called a vertical. The method divides the entire cross section width into smaller increments of approximately equal discharges. The average flow velocity generally occurs at about 0.6 of the total depth, measured from the surface—and the meter is slided along the rod to measure velocity at that depth. The velocity at each vertical should be measured for at least 40 s. The discharge for each increment is calculated as the product of the increment width, depth, and velocity. The total of all of the incremental discharges is the total cross section discharge. In this method, flow discharge is calculated as the sum of the discharge in each increment of channel width:

$$Q = \Sigma\, v\, a$$

Where:

- Q is discharge;
- v is mean flow velocity;
- a is subarea (w x d).

The method, standardized by the USGS is illustrated in a downloadable presentation describing how stream discharge should be measured when wading and using the velocity-area method (Nolan and Shields, 2000): Measurement of Stream Discharge by Wading http://training.usgs.gov/ntc/courses/cbt-cdrom/wrir00-4036.html. Additional information regarding where to set up a sampling station, stage measurement, and control structures. (Nolan, et al., 1998. Surface-water Field Techniques Training Class (v. 1) Water Resources Investigations Report 98-4252) http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/

and in EMAP-SW Streams Operations Manual, Section 6 (Stream Discharge) http://www.epa.gov/emap/html/pubs/docs/groupdocs/surfwatr/field/Sec06.PDF.

Discharge Calculation using Acoustic Doppler Current Profiling (ADCP)

An ADCP is useful to measure discharge in large rivers that cannot be waded. In order to calculate discharge using an ADCP, the device is mounted from a boat with the head of the transducer placed just below the water surface. As the boat travels along a cross section, the ADCP measures flow depth and the velocity along the entire vertical, except for the area near the bed for the channel and the flow surface. Data are regressed using software specific to the instrument. An example of ADCP use is described by Jacobson and Laustrup (2000) for Sturgeon habitat assessment on the Lower Missouri River: http://www.cerc.usgs.gov/pubs/center/pdfDocs/micra_whole.pdf

Discharge Estimation using Float, Tape, and Timer

One additional method to estimate velocity that does not require any instruments except a watch with a second hand and a measuring tape is described in the following:

1. Stretch a tape out for 5 meters along the edge of water in a relatively straight reach of channel. Place the float into the river at the upstream end of the tape. Place the float without throwing or pushing it.
2. Record the seconds between when the float is released at the upstream end of the tape and when it reaches the downstream end of the measured section.
3. Record the elapsed time and the distance measured in a table in your field book. Repeat the experiment several times at intervals across the channel so that the float moves downstream without getting caught in eddies or behind obstacles.

Trial #	**Distance (meters)**	**Time (seconds)**	**Velocity (meters/seconds)**
1			
2			
3			

Average flow velocity is calculated as distance divided by time multiplied by a coefficient, *c*, relating the surface velocity measured to average flow velocity, usually the desired variable. The factor typically used range between 0.8-0.9, depending on the resistance to flow where 0.8 is used for rough streams, and 0.9 is used for smooth channels, however smaller values may be appropriate for very rough channels. Thus, average velocity, v_{av} is:

$$v_{av} = [(v_1+v_2+v_3 \ldots +v_n)/n]\, c$$

where:
v_{av} is the average velocity of the measurements
$v_1 \ldots v_n$ is the surface velocity of trial 1 through n.

Finally, flow discharge is estimated as the product of the surface velocity and the channel cross section area: $Q = A\,v$. This method only provides an approximation of the channel discharge—however, it is useful when you don't have other measuring equipment, or if flow is too high to safely wade across a channel.

APPENDIX II. Methods to Measure Sediment Transport

Key considerations in designing a field-based sediment measurement program are described in detail in Hicks and Gomez (2003). Such considerations must be well thought-out before embarking in a measurement program using methods such as those described in this section. The following provides some resources to evaluate sediment transport using a sediment budget, via routing pathways, and standard methods for field measurement of suspended or bedload and turbidity.

- Methods for development of a sediment budget are described in detail by Reid and Dunne (1996) and Reid (2003).

- Discussion of sediment transport pathways at the watershed scale, or sediment routing can be viewed in the CD: Landscape Dynamics and Forest Management RMRS-GTR-101-CD, 2002 or on-line at: http://www.earthsystems.net/sim.htm.

Field measurements of bed material load, suspended load, and turbidity must be conducted at the same time as discharge measurements are made, using the protocols described in the preceding section. Field measurement of sediment transport including bed material load, suspended load, turbidity is provided in "USGS Field Methods for Measurement of Fluvial Sediment" by Edwards and Glyson: http://water.usgs.gov/pubs/twri/twri3-c2/. Methods and recommendations for monitoring coarse sediment load are provided in Ryan and Troendle (1997): http://stream.fs.fed.us/publications/PDFs/RYAN.PDF. Specific detail relating to the measurement of turbidity and suspended sediment is provided in "Turbidity-controlled suspended sediment sampling" by Lewis and Eads in the Watershed Management Council, Summer 1996 newsletter: http://www.watershed.org/news/sum_96/turbid.html. A guide for measuring water quality is provided in "Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring

Programmes" in a report prepared by UNEP/WHO:
http://www.who.int/docstore/water_sanitation_health/wqmonitor/ch15.htm.

Other sediment sampling methods, such as utilization of bedload traps, tracers, and sediment transport equations are further described in Hicks and Gomez (2003). Use of Optical backscatter sensors to measure suspended sediment transport are described in:
http://www.comm-tec.com/Library/Technical_Papers/Various/cool/4Schoellhamer_Wright.pdf.

APPENDIX III Methods to Calculate Effective Discharge

A Corps of Engineers technical note (Biederharn and Copeland, 2000) illustrates this method to calculate effective discharge for bedload using: 1) a flow duration curve based on mean daily discharges; and 2) bed material sediment load based either on measurements or sediment transport equations. The first step is to calculate the total bed material sediment load (in tons) transported by a flow increment (used in the flow duration analysis) over a period of time. The product of the flow frequency distribution and the bed material load rating curve (in tons/day) are displayed as a histogram that shows sediment load as a function of discharge for the period of record. The peak of the histogram represents the effective discharge.
http://chl.wes.army.mil/library/publications/hetn/hetn-ii-4.pdf.

Further information on this method is provided in:
http://www.nrcs.usda.gov/technical/stream_restoration/PDFFILES/CHAPTER7.pdf and
http://chl.wes.army.mil/library/publications/hetn/hetn-ii-5.pdf.

APPENDIX IV Methods to Assess Substrate and Grain Size Distributions

The Pebble Count Method

1. Measure the grain size of the sediment below your left foot every step down the beach. Use a ruler, calipers, or hand held sieving device (described below) to measure the intermediate diameter of the sediment grain you pick up. The ruler scale should be in mm units.
2. Prepare a table with 10 rows and 10 columns (100 measurements) in your field book and record the data, each measurement in a separate box.
3. Leave a space in your book for another table with the following row and column headers:

Size Class (mm)	Tally	# of Samples in Class	% of total	Cumulative % finer
248 - 360				
180 - 248				

124 - 180				
90 - 124				
64 - 90				
45 - 64				
32 - 45				
22 - 32				
16 - 22				
11 - 16				
8 - 11				
5.6 - 8				
4 - 5.6				
2 - 4				
< 2				
	Total = 100	Total = 100	Total = 100%	

4. Leave the opposite page blank for a graph of the data. Plot sediment grain size (mm) on the x-axis and cumulative % on the y-axis.
5. Now you can use this graph to determine the median particle size (D_{50}) of the sediment distribution. D_{50} is a commonly used indicator of the particle size distribution of the channel bed.

An Excel worksheet to aid in setting up a pebble count and analyzing the data is provided in a “Size-Class Pebble Count Analyzer,” (Potyondy and Bunte, 2004). http://stream.fs.fed.us/publications/software.html. Using a hand held sieving device, or gravel template to measure the size of gravel sized sediment (US SAH-97 Hand Held Particle Size Analyzer) a method described by (Potyondy and Bunte, 2002) helps consistency in measuring the intermediate particle diameter. A sediment grain is pushed through various sized openings, until the smallest opening the grain can fit through is found. A description of the hand held particle size analyzer, guidelines for its applications and a procedure for analyzing the data is present on the web at: http://fisp.wes.army.mil/Instructions%20US_SAH-97_040412.pdf This method, like the pebble count is limited to wadable gravel bed streams.

Field measurements of sediment grains size usually use mm scale. Laboratory analysis such as sieving usually uses phi (ϕ) units (where $\phi_i = -3.3219 \log D_i$, and $D_i = 2^{-\phi i}$). Phi units work well for sand and smaller sized sediment, but is cumbersome for coarse sediment sizes because of the negative sign. Parker and Andrews (1985) introduced the alternative ψ scale, where $\psi = -\phi$ and ψ is a positive number for gravel and larger sized sediment.

APPENDIX V Methods to Assess Morphology

Profiles, Cross sections, and Topography Survey Methods

Profiles, cross sections, and topography describe the physical character of morphology in two and three dimensions. At the reach scale, a longitudinal profile, a view from downstream to upstream (or visa versa), along the “thalweg,” or the deepest part of a river illustrates the type of bedforms present. Parameters analyzed from surveyed profiles include slope. A cross section is a two dimensional view across a channel and the adjacent floodplain, and across secondary channels up to and slightly above the top of the high flow bank or another high water mark indicator. Parameters deduced from cross sections include width and depth, and the width to depth ratio. Topography shows a three dimensional view of a reach and illustrates patterns of erosion and sedimentation.

In a thalweg profile, a tape marks the distance along the channel, and the survey rod is placed in the thalweg at increments so that breaks in slope important to defining the morphology are included. For example, if step-pool bedforms are present, the rod should be placed at both the top and base of the step, and at least at the upstream, deepest part, and downstream end of the plunge pool. If riffle-pool sequences are present, the head and base of the riffle and the deepest part of the pool surveyed along with other points defining the profile provide data to document the "residual" pool, as defined by Hilton and Lisle (1993) used to calculate V*. These points should be labeled in the survey notes. Profiles surveyed along bankfull indicators or the break in slope between the floodplain and channel bank provide data that may be used to calculate channel slope. In a profile, the tape marking distances should be stretched along the centerline of the high flow channel. A way to think about this is that the flows that transport sediment and form the morphology you are measuring occur when the channel is full of water—but most surveys are completed during the low flow season when the thalweg and low flow channel meander within bars and the channel banks. However, the centerline of a meandering low flow channel exaggerates the channel length measurements and computed channel slope (defined as the elevation change over a channel distance) is underestimated.

The cross section should be oriented perpendicular to the main flow direction in the channel when it is full of water at high flow. Breaks in slope important to a channel cross section survey include the top of bank/edge floodplain, any bank full indicators, the break in slope between the base of bank and the channel bed, the top and edge of bars, and the thalweg, among others.

Profiles and cross sections are often surveyed using electronic distance meters, automatic levels, hand levels, or even line levels—although as technology evolves, new methods will become more prevalent. The following discussion begins by describing some of the most basic and versatile methods, surveying with an automatic level, rod, and tape. With these methods, data are recorded in a field notebook. Survey data using an automatic level provides elevation information at a point measured along a tape stretched from one permanently marked endpoint to another along a cross section. Steps 1-11present an overview of the survey process for a channel cross section (using an automatic or hand level):

1. Using the even numbered pages of your field notebook, label the columns as shown to record your survey data. Use the odd numbered pages for notes that you keep on the same line as the data. Above each data set, provide a title: e.g. Cross Section #1 across Pool; or Thalweg Survey.

Setup #	Station #	Distance (m)	Back-sight (m)	Height of instrument (m)	Fore-sight (m)	Elevation (m)	Notes
1	Benchmark		xx	xx		Absolute or arbitrary	Describe the benchmark
					xx	Calculate	Describe where rod is held
					xx	"	"
					xx	"	"
					xx	"	"

2. Select a benchmark.
3. Stretch the tape from bank to bank with 0.0 m on the left bank of the "creek," as you look downstream.
4. The automatic level is set up on the tripod and leveled at a location where the entire cross section, several cross sections, and as much of the profile as possible can be seen, and at a height that is above the cross section endpoints and the benchmark.
5. A rod-person sets the rod on top of the benchmark, the datum for the cross section. The surveyor focuses on the rod placed on the benchmark and reads the rod increment under the long line that appears in the center of the ocular. The note taker records the "back sight," (BS).
6. If the channel bends or a large section of the profile or cross section is obscured by vegetation, you will need to shoot a turning point, before moving the instrument. Record the new setup number in your field notebook in the first column.
7. The height of the instrument (HI) is calculated as: HI = BS + elevation$_{(\text{benchmark})}$
8. The rod person moves the rod across the channel along the tape, the instrument person reads the rod placed along the tape, and the note taker records the foresights (FS). The rod should be placed at every point where the channel cross section changes slope. The level of detail will be determined by the purpose of the field work. For wadable creeks, points should be taken on the order of every 0.5 to 1 m, or so---closer where warranted to represent the top and base of steps or offsets in the channel boundary, and farther apart where the boundary doesn't vary.
9. Close the survey by re-shooting turning points and the benchmark to help estimate of error.
10. Elevation is calculated as: elevation$_{(\text{creek})}$ = HI-FS
11. The cross section plot will show distance (x-axis) plotted against elevation (y-axis).

Harrelson et al., (1994): http://stream.fs.fed.us/publications/PDFs/RM245E.PDF describes two dimensional survey techniques including setting permanent survey benchmarks, surveying cross sections and profiles. Importantly, this document describes a method of accomplishing a “turning point,” a survey technique to tie two segments of a profile or cross section together when moving the instrument is required to see the remainder of the section—something that occurs frequently in forested or heavily vegetated areas or when a profile follows the channel around a bend.

Cross sections intended to document morphology should not be evenly spaced along the reach. Rather, they should be located consistently to describe the features present. For example, in a reach with riffle-pool sequences important for anadromous fish habitat, cross sections might be located over the head (upstream part) of the riffle and over the deepest part and tail (downstream part) of pools—depending on the specific questions being asked. In addition, cross sections may extend beyond channel banks over the floodplain in order to document connectivity between the floodplain and the channel.

Topography from spectral images or aerial photographs provides data of the land surface above the water. Without additional bathymetric data collection, these data are inadequate to document channel or estuarine morphology. Sometimes data presented as channel cross sections actually illustrate the channel banks and the water surface—and repetitive surveys simply show variation in water levels. Care should be taken to understand how the methods of data collection constrain representation of the morphology.

Topographic surveys conducted in the field require an electronic distance meter (total station) or detailed aerial or spectral data, and data are often recorded digitally and downloaded to a computer. Aerial topographic data usually has resolution of 1-2 feet, and is appropriate for documenting morphology where the scale of change is significantly larger than the resolution of the data. Defining higher resolution topography in the field is time consuming, and shorter reaches that define a particular feature, such as a floodplain sand splay and channel complex are sometimes or a short reach for 2- or 3-dimensional modeling studies are typical. Often the survey strategy for model input data includes evenly spaced points surveyed several feet apart that makes setting up a modeling grid easier to accomplish. However, depending on the scale of change and questions being asked about a particular feature, an evenly spaced grid may or may not document the breaks in slope necessary to characterize the feature of interest. If this is the case, permanently marked or monumented cross sections and profiles may also be required in order to provide baseline data for comparison to future surveys. Sections constructed from data collected on a grid are useful when the morphologic features are relatively large.

APPENDIX VI. Classification in Fluvial Geomorphology

Method Summary

In watershed assessment, classification is the sorting of attributes, commonly river morphology, into groups based on some type of common characteristic. Classification provides a way to simplify assessment of complex watersheds by grouping components into sets with common qualities. Stream classification provides a method to categorize river geomorphology so that individual reaches of one river may be differentiated or so that characteristics of rivers in different watersheds may be compared. Many types of river classifications have been developed (e.g. summarized by Kondolf et al., 2003) depending on the nature and scale of the problem and specific character of the watershed system. Several commonly used classifications are compared in this section including geomorphic stream channel classifications (Montgomery and Buffington, 1997; Rosgen 1994), a genetic classification of floodplains (Nanson and Croke, 1992), and a biotic classification of a mountain stream system (Frissell et al., 1996). These examples do not address all of the existing classification systems; instead, they highlight differences in approaches and provide an illustration of watershed attributes that may be classified to aid assessment.

The goal of classification is to help simplify complex environments; however, misuse of classification exercises arise when river attributes do not conform to the classification applied. The purpose of this section is to provide examples that point out an important question to ask: does a particular watershed under investigation fit well into an existing approach?

Questions that can be Answered using Classification and Spatial and temporal scale

Watershed assessment commonly includes investigation of river system attributes. A classification may aid in dividing the river profile into smaller reaches for more detailed investigation. Questions that may be answered using various classification techniques include:

> Does the dominant bedform morphology in a river provide depth, velocity, and grain sizes necessary as the physical structure of habitat for the river-based life stages of salmonids or other anadromous fish?
>
> Does the characteristic grain size of sediment in riffles or pools have the potential to support abundant aquatic invertebrates?
>
> What percent of the channel banks are undercut and provide refuge for young salmonids?
>
> What are the characteristics of floodplains in the area what processes occur as channels and floodplains interact?
>
> Has channel widening that occurred over the monitoring period altered bedform morphology?

The question of whether or not classifying watershed attributes furthers our understanding of the problems we are concentrating on should be addressed before undertaking the classification exercise. The temporal and spatial scale addressed in a classification will vary depending on the specific question being asked. Classification is inherently a static approach, and the time-frame over which it is relevant is dependent on the time-frame of change and evolution of morphologic features classified.

Description of Methods

Stream Channel Classification

Montgomery and Buffington (1997) developed a reach-scale approach to classification of bedforms in alluvial mountain channels in the Pacific Northwest that suggests that the ratio of transport capacity to sediment supply governs channel roughness that influences channel reach-scale morphology. Their classification includes five reach-types:

- Cascade reaches (stream gradient >0.03) form in steep reaches with boulders and cobbles that are not organized in recognizable patterns; large particles are mobilized infrequently, whereas finer sediment moves over the more stable bed material during moderate flows; sediment supply is limited to inputs from adjacent hillslope mass movement.

- Step-pool reaches (stream gradient ranging from 0.03-0.10) form in reaches with boulders and cobbles that are organized in patterns with large boulder and cobble accumulations forming transverse to the flow direction. Water flows over these accumulations and plunges into small pools downstream, forming as stair-step like profile; sediment supply is limited.

- Plane-bed reaches (stream gradient ranging from 0.01 to 0.03) are composed of cobble and gravel that exhibits a relatively featureless topographic profile and represent a transition between supply-limited and transport-limited morphology.

- Riffle-pool reaches (stream gradient ranging from 0.01 to 0.001) are characterized by an undulating gravel bed profile; commonly spaced 5-7 channel widths apart; exhibits both supply-limited and transported-limited characteristics. Gravel is usually transported at near bank-full flow.

- Dune-ripple reaches (stream gradient < 0.001) form in low-gradient sand bed streams where the sand bedform evolves depending on flow depth and velocity. San can be transported at relatively low flow stages; reaches are transport limited.

The descriptions of each the reach types in this classification are based on research by numerous fluvial geomorphologists over the past century and are summarized in detail in many river-related text books e.g. Knighton (1998) and Wohl (2000). To accomplish this type of classification, the practitioner must be able to identify and differentiate reach-type morphology, survey longitudinal profiles to document channel slope, and quantify particle size distributions.

Rosgen (1996) used data from rivers in Colorado, Nevada, and Wyoming to develop a classification system consisting of three levels. Level I is a broad characterization of valley morphology, channel relief, pattern, shape and dimension. Level II is a morphological classification of existing channel conditions with seven categories, designated using an alphanumeric code as type A through type G, based on differences in five parameters: slope, width to depth ratio at bank full flow, sinuosity (the ratio of stream length to valley length), and median bed-surface particle size, and "entrenchment ratio" (the ratio of the width of the flood-prone area inundated by flows having twice the maximum depth of bankfull flow to the width of the bankfull channel). Each of the seven main types has a number assigned that reflects bed material particle size, and a small letter indicating slope, yielding 41 subgroups. Level III uses 10 parameters to describe “stream channel influence variables” including riparian vegetation, streamflow regime, stream size and order, organic debris and/or blockage, depositional patterns, meander patterns, stream bank erosion potential, aggradation/degradation potential, channel stability rating, and altered channel materials and dimensions. These 10 parameters are used descriptively to assess potential vs. existing channel conditions. Rosgen (1996) provides further description of the classification protocol and field methods needed to classify a channel. In order to accomplish the Rosgen classification, the practitioner must be able to document channel morphology using cross section and profile surveys and measure velocity and particle size distributions. The system assumes that a channel is, or should be, adjusted to bankfull as the formative discharge.

Floodplain Classification
Nanson and Crooke (1992) developed a classification of floodplains based on specific stream power, ω,

$$\omega = \Omega / w$$

where Ω, stream power is equal to γQS where γ (equal to the density of water, ρ, times the acceleration of gravity, g) is the specific weight of water, Q is the flow discharge, S is slope. Stream power is an expression for the rate of potential energy expenditure per unit length of channel, or the rate of doing work (Knighton, 1998). The specific stream power,ω is the stream power, Ω divided by channel width, w. Nanson and Crooke’s (1992) floodplain classification defines three categories:

- High-energy floodplains (ω >300 W m^{-2}) composed of non-cohesive sediment, in narrow valleys with little lateral stream migration, where vertical accretion of relatively coarse sand and gravel dominates sedimentation processes.

- Medium-energy floodplains (ω = 10 to 300 W m^{-2}) composed of non-cohesive sediment, in wider valleys where meandering or braiding is common, and where lateral migration and braiding dominant sedimentation processes.

- Low-energy floodplains(ω <10 W m^{-2}) composed of non-cohesive or cohesive sediment, usually associated with laterally stable single thread or multiple channel anastomosing rivers, where vertical accretion of relatively fine sediment and avulsion dominate sedimentation processes.

Data needed in order to calculate the specific stream power in a river include the discharge, slope, and width of the channel adjacent to the floodplain measured at bankfull flow conditions. This calculation is typically accomplished using gaging station data in combination with field surveys.

Biotic Stream Classification
In biotic stream classification, Naiman (1998) suggests including broad spatial and temporal scales, integrating structural and functional characteristics under different disturbance regimes, and communicating information about processes responsible for creating and maintaining stream characteristics. Frissell et al., (1996) documents the organization and scale of a mountain stream system starting at the watershed scale and decreasing in size to microhabitat important for aquatic organisms. This classification is hierarchical in nature, such that each smaller scale class is contained within the next

higher class. The longitudinal boundaries of each class can be distinguished according to the following:

- Stream system, (10^3 m), the 4th to 6th order portion of a channel network within a mountain watershed;
- Segment (10^2m), the length of the main channel between tributary junctions, major breaks in slope, or geologic or structural changes;
- Reach (10^1m), the length of channel between major slope breaks or structures capable of withstanding the 50-year flood;
- Habitat or channel unit , e.g. pool-riffle1(0^0m), length of channel between water surface or bed profile slope breaks;
- Microhabitat (10^{-1}m), zones of differing substrate type, size, arrangement, flow depth and velocity, or vegetation.

Channel units are useful in watershed assessment in order to describe habitat conditions in complex systems. Channel units may extend several channel widths in length, and are the morphologic building blocks of a reach (Montgomery and Buffington, 1998). Examples of channel units include bars, pools, riffles, rapids, cascades, etc.

Benchmarks

In order to prevent channel classification from becoming a subjective exercise, descriptive categories should be avoided. For example, physical components of habitat rated subjectively as “ good,” marginal, “poor,” “low”, “high,” etc cannot be used in monitoring to document channel change, as the definitions are subjective and may vary between the same practitioners from year to year or different practitioners even during the same year. Designation of “riffle,” or “pool” and other channel units may be subjective, subject to bias of the practitioner; moreover, changes in frequency and depth e.g. of pools) may lead to inappropriate management targets and structural fixes (Poole et al., 1997).Quantification of watershed characteristics should be based on repeatable measurements based on standards described in previous sections.

Appropriate use of data/Limitations

A limitation of classification is that it provides a static view of a watershed, nature of natural systems, and because river characteristics follow a continuum so that the boundary between classes is sometimes unclear. As an example, the classification exercise should not be used in a way that forces a system with characteristics of a lowland anabranching floodplain river into a classification system that only addresses single thread meandering floodplain rivers—because the processes that create and maintain these systems are very different. While classification may be a useful tool to help characterize morphology and to organize data, it does not always help understand the dominant processes responsible for creating or maintaining that morphology. When classification of river morphology is used to make management decisions without understanding the processes that lead to its formation and evolution, natural processes may be unexpected and effective management is impossible

Each of the classification systems described in this section has benefits and limitations as a general tool. The Montgomery and Buffington (1997) classification of channel morphology provides a process-based characterization channel bed morphology specific to mountain streams where bedform type has different flow depth and velocity and grain size, and thus, different habitat attributes. Thus, classification of channel reach morphology is a useful tool for assessing the physical structure influencing habitat in many watershed assessments. A limitation of the classification when used outside it’s relevant domain is that it is channel-centric and doesn’t include the floodplain, an important component of lowland fluvial systems. The Rosgen classification is often used beyond characterization of rivers, in order to predict channel change and to develop management or restoration plans. However, limitations of Rosgen’s classification have been noted by geomorphologists (e.g. Miller and Ritter, 1996, Montgomery and Buffington, 1998; Kondolf et al., 2003) as not being linked to a description of the processes responsible for creating the morphology classified, as lacking explanation of the rationale underlying the predictions of channel change, and for introducing complicated codes for standard geomorphic terminology. Because the classification approach assumes that morphology is adjusted to bankfull discharge, application to disturbed channels where morphology is not maintained or created by bankfull discharges is problematic. Naiman (1998) suggests that classification systems are in describing ecological patterns and in developing corresponding management strategies within a watershed. Limitations of Frissell et al., (1996) channel unit classification arise because distinctions between units tend to overlap and change with discharge, and channel unit classification by different observers may yield inconsistent results. Montgomery and Buffington (1998) suggest that while the channel unit scale is biologically relevant, interpretation of the abundance, characteristics, and response potential of channel units depends on which reach type it is associate with, e.g. a pool associated with large woody debris might fill while a pool in a step-pool sequence may be less responsive to a sediment input. Another limitation of this biotic classification is that it is channel centric and doesn’t include habitat function of the floodplain. Nonetheless, when limitations are acknowledged, classification may be useful in helping document various components of the fluvial system in a watershed assessment. Note that none are appropriate for all aspects of rivers in watershed assessment, nor do any qualify as an approach that is applicable in all types of rivers in California; rather each has a specific focus and applicability—and there may not be an existing approach that addresses the unique attributes of the river you are investigating.