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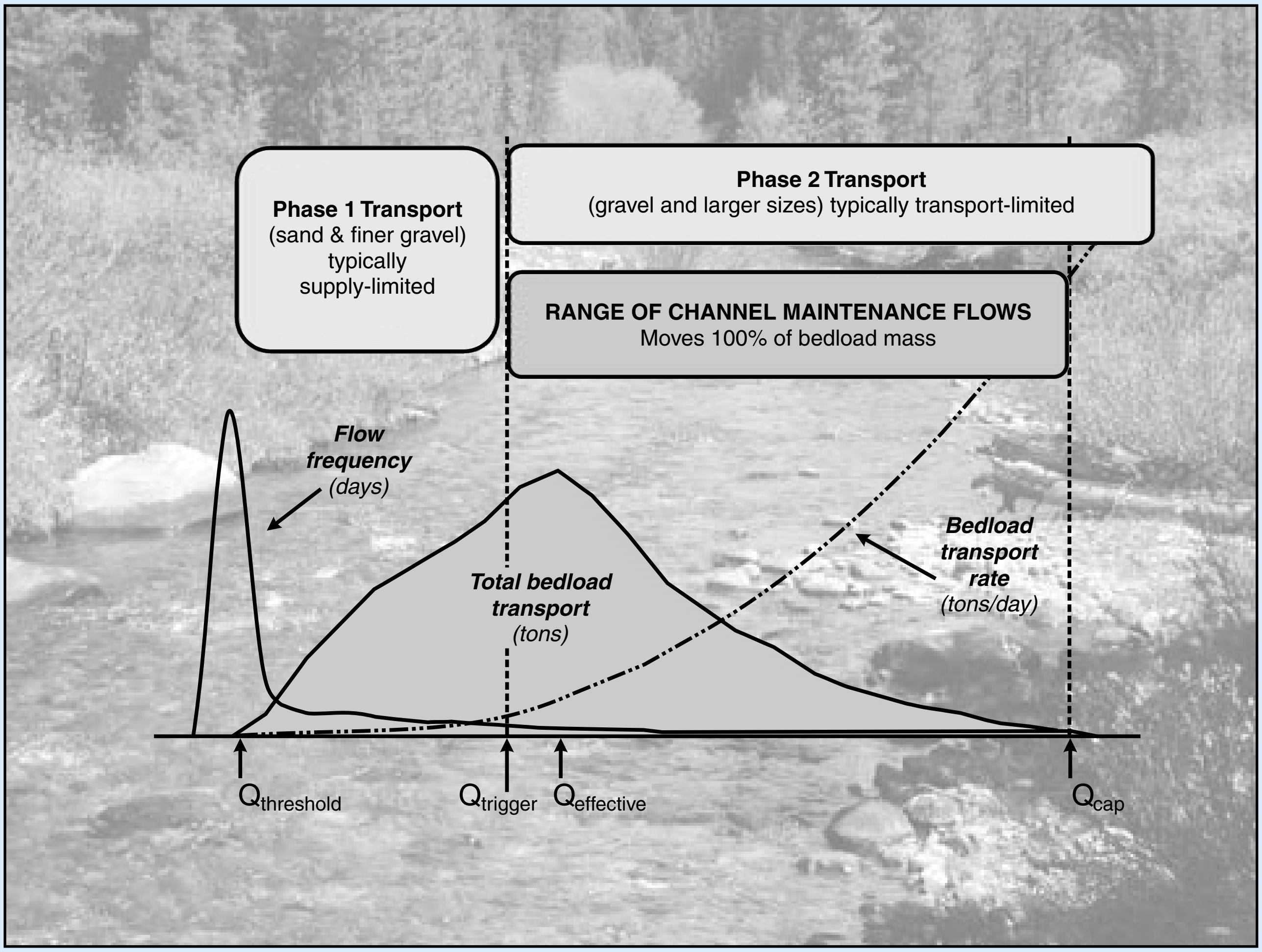
Quantifying Channel Maintenance Instream Flows:

An Approach for Gravel-Bed Streams in the Western United States

Larry J. Schmidt and John P. Potyondy



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Abstract

This paper discusses one approach for quantifying channel maintenance instream flow necessary to achieve the Forest Service Organic Act purpose of securing favorable conditions of water flows. The approach is appropriate for quantifying channel maintenance flows on perennial, unregulated, snowmelt-dominated, gravel-bed streams with alluvial reaches. The approach identifies the minimum essential regime of streamflows necessary for the channel and its floodplain to remain fully functioning with respect to sediment and flow conveyance. The paper discusses the role of water, sediment, and vegetation in maintaining a channel and provides methodologies for estimating the upper and lower limits of the required sediment transporting flows. Conceptually, these flows range from intermediate flows associated with initial coarse sediment movement from the coarse surface layer of gravel-bed streams (Phase 2 transport) up to the 25-year flow event. The paper also provides suggestions for analyzing and displaying results, implementing studies at the watershed scale, determining data needs, and post-project management and evaluation. Best application of the approach occurs at sites having long-term bedload data and streamflow records.

Keywords: gravel-bed streams, channel maintenance instream flows, bedload transport

The Authors

Larry L. Schmidt, Program Manager and Physical Scientist (retired), USDA Forest Service, Rocky Mountain Research Station, Stream Systems Technology Center, 2150A Centre Avenue, Fort Collins, CO 80526-1891.

John P. Potyondy, Program Manager and Physical Scientist, USDA Forest Service, Rocky Mountain Research Station, Stream Systems Technology Center, 2150A Centre Avenue, Fort Collins, CO 80526-1891.

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Natural Resources Research Center
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Fort Collins, CO 80526

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Acknowledgments

The Stream Systems Technology Center has been working on stream channel maintenance issues for over 10 years. During that time, we have consulted with a wide array of scientists in the Forest Service, other agencies, and universities and a large number of National Forest specialists, expert witnesses, and lawyers who have worked with us. We sincerely appreciate the constructive, frank, and thoughtful suggestions and comments provided over the years and have tried our best to develop an approach that is both scientifically sound and readily explainable to non-technical audiences, such as managers and judges. In developing an approach, we take full responsibility for the interpretations we have made and recognize the divergent viewpoints and the many different ways to solve this problem. Helpful review and comments were provided on the most recent draft by Jack King, Tom Lisle, John Buffington, Chuck Troendle, Sandra Ryan, William Emmett, Lois Witte, and Steve Glasser. Their comments greatly improved the quality of the final product. We also wish to acknowledge earlier reviews and helpful thought-provoking comments and discussions provided by Bob Beschta, Luna Leopold, Dave Dawdy, Bill Jackson, Jon Nelson, Ned Andrews, Robert Milhous, John Pitlick, Bill Dietrich, Matt Kondolf, Dave Montgomery, Peter Wilcock, Gary Parker, Peter Whiting, Bob Ziemer, Gordon Grant, Kristin Bunte, Mike Collette, Tim Sullivan, and numerous other individuals with whom we have discussed this issue over the years.

Authors' Note:

The Legal Context of Forest Service Channel Maintenance Instream Flows

This channel maintenance quantification approach identifies an essential regime of water flows representing the minimum quantity and timing of flows needed for the self-maintenance of stream channels on the National Forests. Channel maintenance flows are non-consumptive instream flows specifically designed to maintain the physical characteristics of the stream channel. Effective channel maintenance flow regimes have naturally variable flows of sufficient duration, magnitude, frequency, and timing to maintain channel morphology and streamside vegetation so that the capacity of the channel to convey natural flows is unimpaired over the long-term.

Providing channel maintenance flows responds in part to a stated purpose of the reservation act for National Forests, found in the Organic Administration Act of June 4, 1897 (16 USC 475):

> "... No National Forest shall be established except to improve and protect the forest within the boundaries or **for the purpose of securing favorable conditions of water flows** and to furnish a continuous supply of timber for the use and necessities of citizens of the United States. ..."

The Organic Act of 1897 first defined the purposes for which forest reserves could be withdrawn from the public domain and managed. The Act recognizes the importance of watershed protection to the establishment of National Forests and provides the Forest Service with the authority to administer these lands and to protect and improve valuable water resources. The Act expressly gave the federal government jurisdiction over water usage on National Forest System lands by requiring that all waters within the boundaries of the National Forest be used under the rules and regulations of the United States as well as under the laws of the states (Witte 2001).

Over the years, the federal government has made many attempts to secure federal reserved water rights for instream purposes (Gillilan and Brown 1997). A 1978 U.S. Supreme Court decision, known as United States v. New Mexico (438 U.S. 696), has had the most pronounced effect on the ability of the Forest Service to acquire instream flows for the National Forests. In U.S. v. New Mexico, the Supreme Court narrowly construed the primary purposes for the National Forests to be twofold: maintaining favorable conditions of water flows and production of timber. The Court also concluded that the implied reservation theory could not be used to obtain instream flows to protect recreation, fish, and wildlife.

The stringent test articulated by the U.S. Supreme Court states that an implied reserve water right is found only if water is necessary for the purposes of the reserve, that is, to secure favorable conditions of water flows. Furthermore, the water claimed must be the minimum amount of water necessary to fulfill the purposes of the reservation and no more (Witte 2001).

The term "minimum" has been interpreted to mean the least total amount of water in the long term. Thus, the "minimum" amount necessary varies from year to year depending on the natural flows available to accomplish the purpose in any year. In high flow years, more flow is required, albeit nonconsumptively. In low flow years, little to none of the water is useful for channel maintenance. The net effect of this produces the minimum amount of flow needed in total in the long term.

Within the confines of court imposed constraints, the Forest Service has made instream flows claims for channel maintenance in several Western water adjudications. The claims have necessarily had to be based on the legislative history of the Organic Act and the Agency's subsequent interpretation of the phrase "favorable conditions of water flows" in legal proceedings. As a consequence, channel maintenance claims have been narrowly limited to physical channel maintenance, excluding fisheries and aquatic ecosystem considerations.

The United States has typically asserted that amounts of water fully capable of transporting all of the sediment loads from the headwaters to valleys downstream of forest boundaries in alluvial channels, maintaining channel conveyance capacity, and maintaining protective watershed vegetation are essential parts of "securing favorable conditions of water flows" consistent with the Organic Act. While some courts have agreed that stream integrity is a favorable condition of water flows, they have ruled against the United States based on other factual and legal considerations. The Forest Service continues to develop approaches that support reserved water right claims based on the primary purposes of the Organic Act, the "securing of favorable conditions of water flows."

The approach described in this document has been specifically developed within this limiting framework. Application in cases involving the reservation principle must necessarily be constrained to the primary purposes related to the establishment of National Forests. The limitations imposed on the Forest Service have little influence on the technical merits of the approach and the fundamental concepts can be adapted and applied as part of a broader ecosystem context for addressing instream flow needs by others.

Executive Summary

This channel maintenance quantification approach identifies the scientific basis and a methodology for estimating essential water flow regimes needed for the self-maintenance of stream channels. The Forest Service must estimate essential instream flows because increasing demand for future off-stream uses such as irrigation and municipal water supply threaten to deplete critical portions of instream flows on the National Forests.

We hypothesize that channel maintenance flows, coupled with proper management of upland watersheds, will provide for favorable conditions of water flows. We recognize, however, that successful watershed management requires a holistic approach involving management of the uplands as well as stream channels and their flow regimes. Favorable flows occur when the stream channel is able to pass sediment in equilibrium so that aggradation doesn't significantly increase flood peaks. To provide for favorable flows, it may be necessary to legally or administratively secure essential portions of the natural streamflow in National Forest streams. These non-consumptive flows, known as **channel maintenance instream flows**, are designed to maintain the physical characteristics of the stream channel critical to unimpaired flow and sediment conveyance. Because they are nonconsumptive, except for losses due to evaporation and transpiration, the water flows through the protected reach and is available for other uses, both instream and offstream.

The approach herein describes one way to estimate the minimum essential regime of streamflows necessary for the channel and its floodplain to remain fully functioning with respect to sediment and flow conveyance. A stream channel in a fully functioning condition conveys water and sediment without aggradation or degradation, dissipates energy, reduces flood peaks, sustains flows, and otherwise acts as a natural stream.

Appropriate Scope of Application

This approach is appropriate for quantifying channel maintenance flows on perennial, unregulated, snowmelt-dominated, gravel-bed streams with alluvial reaches. Many of the concepts and principles presented have potential application to rain-dominated and other systems, but they must be extrapolated carefully to these systems. The approach is unlikely to work in arid environments with ephemeral channels where hydrographs are flashy.

This proposed channel maintenance flow methodology is primarily intended to evaluate run-of-the-river projects that pass most or all bedload sediment in the natural stream channel. Channel maintenance flow regimes below large storage reservoirs or hydropower facilities, while they include management objectives of moving sediment and maintaining streamside vegetation, require different analysis techniques to address the wide variety of possible ecological or management conditions that may exist.

Reliance on Natural Processes

This approach recognizes the fundamental importance of natural processes in maintaining channels. From a practical viewpoint, retaining essential portions of the natural runoff processes provides the most practical and cost effective means of achieving natural self-maintaining stream channels on National Forest System lands. Artificially maintaining channel capacity and riparian vegetation by periodic channel dredging, concrete lining, or irrigation is technically, economically, and environmentally infeasible to protect extensive channel networks.

Channel maintenance flows are intended to maintain channel function. Remedying upstream disturbances or protecting the channel from cumulative upstream effects of such disturbances requires more than channel maintenance flows. Channel maintenance flows seldom, if ever, reverse past channel disturbances and impacted systems may, in some circumstances, fail to fully attain the "favorable flows" condition without additional intervention on the landscape or in the stream channel.

Alternative Channel Maintenance Flow Approaches

Many approaches that deal with maintaining channel form and processes have addressed channel maintenance flows in natural channels (Reiser and others 1985, 1989; Milhous 1986; Rosgen and others 1986; Andrews and Nankervis 1995; Leaf 1998; Emmett 1999; McNamara and others 2000). Other approaches with broad geomorphic and ecosystems-based perspectives have also been presented (Hill and others 1991; Jackson and Beschta 1992; Ligon and others 1995; Whiting 2002). None of these provide a comprehensive methodology for estimating the essential flow regime needed for channel maintenance on National Forest streams.

The approach presented here differs from the above approaches in that it specifically addresses Forest Service channel maintenance needs focusing on transporting all supplied sediment with a minimum amount of streamflow. It also includes maintaining streamside vegetation as an integral part of the required flow regime since naturally stable channels always have abundant streamside vegetation. The approach is based on current scientific knowledge and represents an operating hypothesis that will need to be tailored to specific reach and site characteristics. The methodology will continue to be refined as knowledge about flows and their relationship to sediment transport and streamside vegetation improves.

Summary of Water Needed for Channel Maintenance

Channel maintenance in gravel-bed streams requires a range of instream flows that transport bedload sediments through the channel network. This flow regime prevents stream constriction by in-channel sediment deposition and/or in-channel vegetation establishment. The range of flows also provides sufficient high and low flows to sustain vital channel bank and streambank and floodplain vegetation.

Our analysis indicates that in coarse-grained gravel-bed streams of the Rocky Mountains, low flows that occur most of the year transport insignificant bedload sediment. However, when higher flows begin to fill the channel near its capacity, coarse bedload transport and scour of vegetation within the channel combine to help maintain channel morphology. In addition, these high flows periodically inundate the floodplain, helping to sustain and regenerate streambank and floodplain vegetation. Consequently, a range of intermediate to high flows that typically occurs for a limited time during the year provides for the necessary stream channel maintenance.

Our analysis further shows that over the long term, approximately 20 percent of the annual streamflow is necessary for channel maintenance in gravel-bed channels located within Western snowmelt-dominated watersheds. During extremely wet years, when much of the sediment transport occurs, up to 50 percent of the annual stream flow may be needed. However, during many low flow years, as little as zero percent may be needed, because flows capable of transporting bedload sediment fail to occur. Each site has unique requirements and results may differ from this range of numbers. Interestingly, satisfying the channel maintenance needs results in a roughly even flow being available to off stream uses in any given year.

Implications for Water Users

The proposed channel maintenance flow allocation has a negligible effect on most existing water rights, particularly senior water rights downstream of National Forests. In snowmelt-dominated systems, most water needed to maintain the channel occurs during spring runoff, and a large share of channel maintenance needs can be met during wetter years. Channel maintenance flows may limit future opportunities for diversions and storage within the National Forest.

Forest Service Application of This Methodology

This channel maintenance methodology can be used to analyze instream flow requirements for water rights adjudications, water rights negotiations, Forest Planning applications, or evaluating water diversion or storage projects that might adversely alter natural flow regimes. The Forest Service generally applies this methodology in two settings:

1. **Water adjudications, water negotiations, and Forest Planning** where the approach is used to estimate the instream flow needed to fulfill the Forest Service's Organic Act mandate, and

2. **Special use permits, easement stipulations, and licenses** for authorized water diversions and impoundments on National Forest System lands where the approach is used to estimate the minimum streamflows that must remain in the channel as a term and condition during the grant of a special use authorization.

Quantifying Channel Maintenance Instream Flows:

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Introduction

Leaving a portion of the natural streamflow in the channel satisfies numerous physical and ecological functions. Instream flow regimes are commonly quantified to provide instream water essential for recreational opportunities and aesthetics, to maintain habitat features for fish and other aquatic biota, or to maintain floodplains, riparian vegetation, and the channel itself.

This channel maintenance flow quantification approach is designed for gravel-bed rivers. It identifies essential water flows needed for the self-maintenance of stream channels with the smallest amount of water necessary to achieve the Organic Act purpose of providing for favorable conditions of water flows. Failure to provide channel maintenance flows adversely affects the stream channel, floodplains, and streamside vegetation within years or decades.

Benefits of Channel Maintenance Flows

While everyone appreciates the benefits of clean drinking water and food grown with irrigated water, the benefits of channel maintenance flows to environmental systems are less readily apparent but equally important.

Channel maintenance flows provide these benefits:

- Convey water and erosion products from tributary areas through the stream system without aggradation or degradation,
- Maintain the relationship between the channel and the floodplain by temporarily storing flood flows on the floodplain,
- Maintain the ability of the stream to dissipate energy on the floodplain,
- Maintain essential channel capacity to avoid increasing flood risk to adjacent and downstream facilities,
- Maintain pools, riffles, meanders, and other physical habitats necessary to sustain aquatic ecosystems,
- Provide pools as sources of water for fire suppression and escape areas for firefighters, and
- Provide navigation conduits on larger streams and rivers to provide for recreational floating and power boating.

Healthy streambank and floodplain vegetation, commonly referred to as riparian areas, are a key factor in maintaining channels by providing:

- Roots to bind and support banks and reduce bank erosion,
- A vegetation filter that removes and stabilizes sediments and nutrients moving toward the stream from adjacent slopes,
- Surface roughness on the floodplain favorable for recharging groundwater systems,
- Effective floodplain soil conditions to detain flood water for later release to sustain low flows,
- Moist corridors that act as natural fuel-breaks, fire line anchor points, and safety zones,
- Large woody debris which creates log-steps and other structural features that form pools and bars, and
- Shade to the stream that maintains cool water temperatures necessary to sustain cold-water aquatic life.

Consequences of Failing to Provide Necessary Flows

Natural self-maintaining channels are the goal of this channel maintenance approach. Desired channel maintenance occurs when the flow regime can transport the quantity and sizes of sediment imposed on the channel without aggrading or degrading the channel over the long term.

Failure to convey the water and erosion products from tributary areas through the stream system causes sediment to accumulate in the channel. Accumulations are most severe in low gradient adjustable channels and those with high sediment input from tributary channels or valley walls. The accumulated sediment reduces channel capacity and provides sites favorable for vegetation establishment within the channel. We hypothesize that the greater the extent of the accumulation and vegetation encroachment in the channel, the higher the likelihood of increasing the elevation of future floods and thereby increasing flood damage to streamside resources or property.

In some cases, accumulations of sediment and debris may block the channel resulting in high flood surges of debris and sediment. Natural disturbance events (landslides, fires, etc.) occasionally deliver large quantities of sediment and wood to the channel, and these hillslope processes continue irrespective of the condition of the downstream channel. In the absence of natural stream flows, channel blockages may develop and be breached with catastrophic downstream consequences when infrequent large floods occur. These large floods may scour the channel at one time, deliver undesirable quantities of sediment downstream, and produce channel incision that drains groundwater.

Failure to maintain streamside vegetation can change vegetation composition and reduce plant density. Decreased streamside vegetation can lead to increased bank erosion and accelerated delivery of sediment to the channel since the ability of roots to bind soil in the streambanks is reduced. Streamside and floodplain vegetation also temporarily detains flood flows on the floodplain. Gradual release during the low-flow period stretches out water availability for downstream users.

Premises

Scientists have observed and investigated natural alluvial channels for many years. From these studies and body of literature, a series of premises have evolved that describe channels and the processes responsible for their behavior.

Channels and streams exist in nature. They have a form that varies across the landscape and characteristics, such as pools, riffles, and meanders, which repeat themselves within the channel. These channels have formed in alluvium without human interference; from this we conclude that natural streams are self-formed.

Channels are a vessel for conveying water and erosion products. This vessel has sides (banks) and a bottom (bed). Channels are part of a natural watershed system that supplies both water and sediment to the stream and carries it downstream.

The flow sequences that forms channels vary in timing and quantity over the long-term. The variable nature of flows, geology, climate, and vegetation results in a consistency of self-formed channel features that repeat themselves given similar conditions. From this we conclude that common processes are involved in creating and maintaining the channel forms observed in nature.

The water confined in channels periodically moves the sediments that form the bed and banks of channels. The water in the channel also flows over the adjacent floodplain. Therefore, the floodplain is an extension of the channel.

The floodplain supports typical streamside vegetation. Abundant streamside vegetation along streams is a common feature of many natural systems. The streamside and floodplain vegetation co-evolved with the current physical environment and water regime.

A certain quantity of water is necessary to transport the bed material and erosion products entering the channel network and thereby maintain channel form. These self-formed channels have certain characteristics regarding width, depth, and bank height that developed under the current climatic regime.

We understand alluvial channels to some degree. For example, it is evident that the channel adjusts its width and depth in response to changes in flow and sediment regime. Commonly accepted generalizations about alluvial channels include:

- The general form of the channel persists in the current climatic regime.
- Flows reaching or exceeding the top of the bank (bankfull) are attained with moderate frequency—on average every year or two.
- Bankfull flows completely fill the principal channel to the elevation of the floodplain.
- Bankfull flows move some of the material on the bed of the channel.

We understand vegetation-flow relationships to some degree. A complete understanding of the effects of streamflow regimes on specific vegetation communities is lacking. However, in general all streamside vegetation depends on the hydrologic flow regime to some significant extent.

- Streamflows provide a source of abundant moisture.
- Streamflows transport seed and propagules.
- High flows deposit sediment and scour areas of the floodplain creating and maintaining regeneration sites.
- Flows in the main channel suppress vegetation growth in the channel by several mechanisms including scour and inundation.

The flow regime needed to maintain the channel depends upon the amount and sizes of sediment entering the channel over the long-term. To exist, a channel reach must convey all the mass and sizes of alluvial sediment supplied over time. Otherwise, the unconveyed incoming sediment load will accumulate. The best evidence of the largest sizes of sediment periodically moved is the size of particles on the surface of active in-channel bars. Discharges needed to move these larger particles often occur at flows near bankfull discharge. Because bedload transport rates increase rapidly with greater but less frequent discharges, in the long-term a relatively small volume of water moves a high percentage of the bedload.

Source: A conversation with M. Gordon "Reds" Wolman, Dept. of Geography and Environmental Engineering, Johns Hopkins University (personal communication 1996).

Scientific Basis

This section discusses what science tells us about the role of water and sediment in forming and maintaining gravel-bed streams, the importance of streamside vegetation to these processes, and the adverse consequences likely to result from a lack of channel maintaining flows.

We define channel maintenance flows as non-consumptive instream flows specifically designed to maintain the physical characteristics of the stream channel. We hypothesize that stream channels function properly when they support vegetation typically adapted for life along the stream and have naturally variable flows of sufficient duration, magnitude, frequency, and timing to maintain channel morphology so that the capacity of the channel to convey natural flows is unimpaired over the long term.

Channel maintenance defined in this manner involves more than maintaining the channel as a conduit for sediment. Essential attributes of a properly-functioning, self-maintaining channel include:

- Moving all the mass and sizes of alluvial sediment supplied to the channel,
- Maintaining channel capacity by preventing vegetative growth in the bed of the channel,
- Scouring the channel bed to reshape alluvial features,
- Providing for lateral migration within the stream corridor,
- Periodically inundating the floodplain, and
- Protecting and sustaining channel banks and the floodplain by maintaining healthy streamside vegetation.

The Role of Water and Sediment in Maintaining a Stream Channel

Fluvial geomorphic processes are fundamental for determining the structure and function of river ecosystems and maintaining their dynamic morphology (Ligon et al. 1995; McBain and Trush 1997; Trush et al. 2000). A basic premise of fluvial geomorphology is that stream channels adjust to transport the sediment and water supplied to the channel by the drainage basin (Leopold 1962). The shape of the channel is controlled by a number of factors including the magnitude and duration of formative flows, the character of the transported sediment, and the composition of the bed and bank, including vegetation (Leopold et al. 1964).

Gravel-Bed Rivers

Alluvial rivers can be broadly classified as gravel-bedded or sand-bedded (Simons and Simons 1987). Gravel-bed streams and rivers have unconsolidated particles, with median sizes larger than sand (>2 mm) and a coarse channel-bed surface layer that overlays a finer subsurface layer.

Like all alluvial rivers, gravel-bed rivers continually adjust their geometry, surface texture, pattern, and slope in response to the imposed particle sizes, sediment load, and discharge to make transport rates match input rates. Although natural streamflow varies considerably, a channel's average morphology varies considerably from section to section but stays predictably the same even while migrating laterally within the river corridor. Significant bedload transport in gravel bed-rivers typically begins at intermediate discharges approaching bankfull flow (Carling 1995). Over a period of years, the sediment load supplied to a channel is transported by the available discharge. For a channel to maintain its morphology over moderate time scales (10 - 100 years), sediment inflow must equal sediment outflow.

The consistency in the behavior of alluvial channels was first demonstrated by Leopold and Maddock (1953) in terms of average hydraulic geometry. Downstream increases in depth, width, and velocity relative to increases in discharge were similar for rivers of different size and in different settings, demonstrating a remarkably consistent channel form, from one river to another and from one cross-section to another (Leopold 1994). From this it follows that the form of a channel is the result of predictable channel-forming processes and that the channel is self-maintained.

Channel Form and Maintenance: The Bankfull Concept

Wolman and Leopold (1957) concluded that flows near bankfull discharge (the discharge which just begins to inundate the floodplain) largely control the form of alluvial channels. Dunne and Leopold (1978) summarized this viewpoint:

> "Bankfull stage corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels."

Although bankfull flows commonly move the largest single increment of sediment, flows below and above bankfull are also needed to convey all of the mass and sizes of sediment supplied to a gravel-bed river.

A bankfull channel continually migrates across its floodplain by eroding material from the outside bank of meander bends and depositing material on the inside of meander bends (Leopold et al. 1964). An interrelated feedback mechanism involving bankfull discharge, a bankfull channel, and its floodplain creates and maintains this dynamic channel form (Parker 1978; Andrews 1984). Flows at or near bankfull are confined by channel banks sufficiently to mobilize and transport bed material frequently. However, as flows begin to exceed bankfull stage, they are no longer confined and flow depth and mean velocity increase less rapidly, thereby reducing the potential for high discharge to cause catastrophic channel damage. This feedback process helps to maintain equilibrium in the channel form.

Leopold and others (1964) observed that bankfull discharge occurs frequently (on average, two out of every three years). Wolman and Leopold (1957) suggested a common recurrence interval of one to two years for bankfull discharge in humid temperate streams but acknowledge that recurrence intervals for some sample sites diverge from these values. The concept of a universal recurrence interval for bankfull discharge has been questioned by numerous investigators (Kilpatrick and Barnes 1964; Harvey 1969; Gregory and Walling 1973; Hey 1975; Williams 1978; Richards 1982; Knighton 1998). Thus, the users of this approach must be aware that there are exceptions to the general rule.

Channel Form and Maintenance: Magnitude-Frequency Concepts

Wolman and Miller (1960) hypothesized that a range of intermediate high flows, rather than bankfull discharge alone, forms the channel and effectively transports the most sediment. They recognized that although the highest floods transport the most sediment per event, the more frequent, lower magnitude floods transport more sediment over the long-term. Discharge frequency times the amount of sediment transported by each discharge defines the long-term sediment transport curve over the entire flow regime (figure 1).

A range of intermediate flows near the peak of Curve C ("effective discharge") transports more sediment over the long-term than either higher or lower discharges. Low discharges (Curve B) cannot transport significant amounts of bedload sediment even though they occur much of the time. Higher flows become more efficient at transporting bedload because doubling discharge more than doubles sediment transport rate (Curve A) in most streams. However, high flows rarely occur, so the amount of bedload moved in the long term is small. Wolman and Miller (1960) further noted that bankfull discharge and effective discharge usually have similar values.

The conclusion that effective discharge is generally approximated by bankfull discharge is supported by studies of gravel-bed rivers in the western United States and elsewhere (Emmett 1975; Andrews 1980; Webb and Walling 1982; Emmett and Averett 1989; Leopold 1992; Andrews 1994; Troendle and Olsen 1994; Battalla and Sala 1995; Troendle et al. 1996) although there remains disagreement over the universality of this relationship (Pickup and Warner 1976; Richards 1982; Ashmore and Day 1988; Nash 1994). Considerable ambiguity in the literature arises from variability in how effective discharge is computed, limited flow records, and difficulties associated with field identification of bankfull stage (Knighton 1998). Recent work by Emmett and Wolman (2001) suggests that the steeper the bedload transport curve, the more important are large flows in transporting bedload, and the larger effective discharge becomes.

The Importance of Bedload

Although suspended sediment usually constitutes more of the total sediment load than bedload, suspended sediment has a less important role in structuring the morphology of gravel-bed channels Gomez 1991; Leopold 1992). Because of the critical role bedload transport has on channel morphology in gravel-bed rivers, this approach uses only bedload transport curves in recommending maintenance flows.

Bedload transport mechanisms are incompletely understood in spite of their importance to channel form. Bedload movement is episodic and discontinuous, fluctuating rapidly within several hours or minutes (Custer et al. 1987; Gomez et al. 1989; Bunte 1996; Leopold and

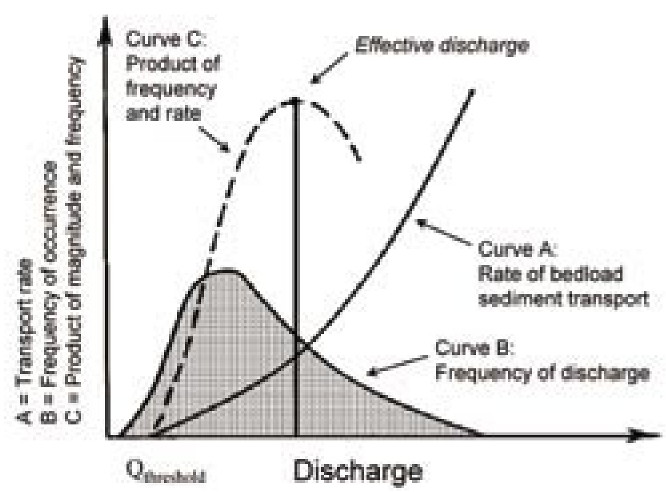

Figure 1—The magnitude-frequency concept applied to bedload transport and discharge (adapted from Wolman and Miller 1960). The concept suggests that a range of intermediate flows transports more sediment over the long-term than either high or low discharges. $Q_{threshold}$ refers to a threshold discharge at which bedload transport begins.

Emmett 1997). Highly variable transport is influenced by numerous factors including variations in stream power along a reach, sporadic sediment input from outside the channel, local bank erosion, turbulent velocity fluctuations, and other temporary imbalances in the sediment budget over short spatial and temporal scales.

In general, smaller particles are moved more frequently than the larger particles comprising the channel bed. The frequency depends on the hydrologic regime and the relative abundance of fines. Slope and grain size are related and both decrease in larger drainages as discharge increases. One reason upland channels are so resistant to change is that they have a wider range of particle sizes in the bed and most of the load is selectively transported over the coarse surface with little change in storage. As a result, larger magnitude, less frequent flows, are needed to rework the bed of mountain rivers with coarse substrates (Baker 1977; Lisle 1987; Carling 1988; Grant et al. 1990; Lisle 1990; Rhoads 1992; Knighton 1998).

The sediment load of gravel-bed rivers typically contains fine sediment that is mobile over a large range of flows. This fine load is often supply-limited, i.e., transport capacity is greater than supply. Fine particles comprise a significant portion of the annual bedload and must be moved through the system to maintain channel capacity and equilibrium (Leopold 1992). Gravel-bed rivers also contain coarse sediment mobilized only during higher flows. This coarse load is often transport limited, i.e., transport capacity is less than supply. Most particles in the channel bed of gravel-rivers are entrained by discharges equal to or less than bankfull stage although the transport rate of some sizes is low and sporadic (Andrews 1983; Pitlick 1988; Leopold and Rosgen 1991; Leopold 1992; Buffington 1995; Leopold and Emmett 1997).

Phases of Bedload Transport

Emmett (1976) first suggested two distinct phases of bedload transport in armored channels. This concept of phases has subsequently been expanded to describe bedload transport in gravel-bed rivers (Jackson 1981; Jackson and Beschta 1982; Beschta 1987; Ashworth and Ferguson 1989; Warburton 1992; Andrews and Smith 1992). Recent studies have confirmed that intermediate discharges transport mainly sand whereas discharges near or above bankfull transport coarser bedload (Church et al. 1991; Komar and Shih 1992; Kuhnle 1993; Carling 1995; Lisle 1995; Wathen et al. 1995; Petts and Maddock 1996; Wilcock and McArdell 1997; Whiting et al. 1999; Ryan and Emmett 2002; Church and Hassan 2002).

Phase 1 sediments are surface deposits of sand sized particles or fine gravel located primarily in pools, along channel edges, and behind obstructions in riffles. Phase 1 Transport signals the initial mobilization and transport of fine bedload over the relatively coarse channel bed surface. Ryan and Troendle (1996) concluded that Phase 1 Transport begins at flows between 0.33 and 0.5 of bankfull discharge in coarse-grained channels on the Faser Experimental Watershed in Colorado. Similarly Emmett (1975) found transport begins at the minimum of annual peak flows (about 0.4 bankfull) for streams in the Salmon River drainage in Idaho.

Phase 2 Transport is associated with the initial coarse sediment movement from the coarse surface layer and underlying channel bed. As flow increases, bedload becomes progressively coarser as a greater proportion of the material is mobilized intermittently and non-uniformly from the armor layer. This has significance to channel morphology. As the armor layer becomes mobilized, finer substrate is also made available, rapidly increasing both the rate of bedload transport and the sizes of bed material in transport (Emmett 1984; Gomez 1983; Sidle 1988; Ashworth and Ferguson 1989; Warburton 1992; Ryan et al. 2002). Phase 2 Transport appears to occur once every one to two years (requiring flows approaching bankfull discharge).

Phase 2 Transport initiates nonuniformly throughout the channel and may be a localized phenomenon as evidenced by the entrainment of bed material from riffles (Jackson 1981) and the nonuniformity of particle sizes and local shear stress (Seal and Paola 1995; Lisle et al. 2000). Conceptually, Phase 2 transport is similar to partial transport (Wilcock and McArdell 1993, 1997) which argues that as flows increase, first selective transport occurs, followed by partial transport when all sizes, but not all particles, are moved. This is followed by full mobility whereby all rocks are moved during the event, not all at once or uniformly, but at different times from different patches. At flows between 50 and 70 percent of bankfull discharge Haschenburger and Wilcock (2003) found about 60 percent of the bed in a state of partial transport, with full entrainment of nearly all grain sizes occurring at flows approximately equal to the bankfull discharge.

Although the beginning of Phase 2 Transport occurs over a narrow range of discharges, precise identification of the discharge at initiation is difficult. Buffington (1995) suggested using flows near bankfull as a first approximation for the onset of gravel transport. Others have found that Phase 2 Transport generally begins at discharges between 60 to 100 percent of bankfull discharge (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker

Summary of the Scientific Basis for Channel Maintenance Sediment Transport Flows:

- Inflow of sediment must equal the outflow of sediment for the channel to be maintained over the long term.
- Bedload transport is of greater importance to channel formation and channel maintenance than suspended sediment in gravel-bed streams.
- All flows capable of transporting bedload sediment are important to channel morphology.
- The magnitude-frequency concept shows that intermediate discharges (for reference, flows near bankfull/effective discharge) transport more sediment overall than other flows in gravel-bed channels.
- The flow threshold of coarse bedload sediment transport begins at less than bankfull/effective flow when a significant portion of the gravel bed mobilizes.
- Because higher flows transport more tons of bedload sediment per unit volume of water, they are more efficient at transporting bedload sediment.
- To transport all bedload over the long-term using natural flows, the natural duration of a range of intermediate to high flows are needed to assure transport of all of the mass and sizes of bedload (i.e., high flows by themselves lack sufficient duration and frequency to transport the entire load).

1997; Ryan et al. 2002; Trush et al. 2000; Ryan et al. submitted).

The beginning of Phase 2 Transport in gravel-bed rivers is significant to channel maintenance because it begins the important process of significant sediment movement of the sizes of material making up the bed and banks of the channel. Consequently, we hypothesize that processes occurring during Phase 2 Transport dominate channel morphology and function in gravel-bed rivers. Retaining flows adequate to achieve and exceed Phase 2 Transport begins to provide the minimum flows needed to achieve channel maintenance objectives.

The Role of Streamside Vegetation in Maintaining a Stream Channel

A properly functioning channel requires a flow regime that not only conveys water and sediment, but also maintains adequate streamside vegetation to protect the integrity of channel banks and floodplain while at the same time keeping the channel proper free of perennial vegetation. This seemingly contradictory role occurs because a natural tension exists between vegetation and flows in the channel. Plants continually attempt to establish and occupy any viable moist surface. Success results in dense vegetation and abundant roots that serve to protect channel banks from the forces of flowing water. Water has a positive influence on vegetation because it provides the moisture plants need to survive, but water also inundates and scours vegetation that lies within the active channel. The negative side of plant growth from the viewpoint of channel maintenance is that vegetation may become established on sediment deposits within the channel during periods of low flow, reducing the ability of the channel to convey sediment and flood waters.

Important vegetation-related physical factors for maintaining the channel are the role plant root systems play in binding soil in the banks and the way floodplain vegetation slows water velocity during overbank flows, thereby trapping sediment and maintaining the floodplain elevation. Streamside vegetation along the active boundary of the channel has the most impact on bank stability (Thorne 1990) and therefore is particularly important to channel maintenance of rivers and streams.

Keeping the Channel Free of Perennial Vegetation

Vegetation constriction refers to the narrowing of a stream channel by perennial woody vegetation within the bed of the channel that is normally devoid of plants. Channels experiencing the normal range of streamflows are rarely constricted by vegetation, but channels with significant diversions may undergo vegetation constriction. Vegetation constriction becomes undesirable when the extent of the vegetation impairs flood capacity and elevates floodwater levels.

Prevention of vegetation encroachment into stream channels involves a combination of hydrologic, geochemical, and fluvial processes. The maintenance of active unvegetated channels involves all or some combination of the following: (1) prevention of germination of seeds and the establishment of seedlings in the channel, (2) the elimination of individuals that do get established in the channel, and (3) the maintenance of conditions that inhibit plant growth and prevent vegetative spread (rhizomes, root sprouts, vegetative propagules) of existing riparian plants into the channel. Because of the range of requirements and tolerances of riparian plant species, it is difficult to generalize or to identify specific conditions that maintain channels free of vegetation, but the primary processes that prevent encroachment are well-understood and are briefly summarized below.

Germination of seeds and the establishment of seedlings in the channel is inhibited by submergence of available seedbed sites at the time when the seeds of likely colonizers are dispersing. Seeds are prevented from reaching sites suitable for germination and growth when the surfaces suited to germination and growth are inundated. Conversely, seeds do land on sites that are suited to germination and growth, but conditions rapidly change following seed deposition (i.e., the site rapidly dries out, becomes too saturated, or is inundated) and recruitment is unlikely to occur. For example, if substrate is coarse and seedlings require a slow rate of groundwater decline to survive, a rapid stage decline would be likely to eliminate those seedlings through rapidly draining substrates. This would cause desiccation of those seedlings with high water requirements resulting in high seedling mortality (Mahoney and Rood 1998).

If seeds are deposited on sites suitable for germination, the conditions of such sites must also be suitable for seedling survival for recruitment to occur. If such an area is subsequently re-submerged, scoured, or buried by sediment, the likelihood of seedling survival diminishes (Van Der Sman and others 1993). Also, if other factors such as soil chemistry, texture, light quality, the length of time between flooding (or flow duration of the surface) are inappropriate for survival of seedlings, then even germination and seedling establishment is unlikely to result in long-term survival of an individual on a site. The wider the range of tolerances of a particular species, the higher likelihood it is that it will be able to persist through the seasonally changing conditions along an active stream channel. This is one reason annuals and generalists (ruderal species, annuals, and invasive weeds) are more common in streamside habitats than in upland areas.

Conditions that inhibit plant growth and prevent vegetative spread (rhizomes, root sprouts, vegetative propagules) of existing riparian plants into the channel include: rapid stage changes that include prolonged inundation of streamside area followed by drought conditions (common along arid-land streams); prolonged inundation that results in anoxic conditions in stream channel substrates; and flooding at more frequent intervals than those required for successful establishment of individuals in the channel (Keddy and Ellis 1985; Cronk and Fennessy 2001). In addition, mechanical disturbances in the channel that are of a magnitude sufficient to either mobilize bed material or to remove above ground biomass (stems, leaves) and uproot individuals are also key factors in maintaining channels free of vegetation (Friedman and Auble 1999).

Maintaining Streamside Vegetation Along the Channel

The composition and structure of streamside vegetation is dependent on the occasional occurrence of seasonal flood flows and subsequent water level declines that maintain moist substrates (Jackson et al. 1987; Stromberg et al. 1991; Mahoney and Rood 1993). The magnitude, duration, timing, and frequency of streamflow can have a profound effect on streamside vegetation, in turn substantially influencing channel dynamics (Gebhardt et al. 1989; Gregory et al. 1991; Hill et al. 1991; Jackson and Beschta 1992). The relationship is complex because riparian vegetation depends on combinations of surface water, shallow groundwater, and precipitation. These factors vary depending on the geologic and geomorphic setting, the species and its characteristics, and the position of the plant on the floodplain (Stromberg and Patten 1996). Flows above bankfull provide for streamside vegetation needs by inundating the floodplain, encouraging floodplain scour and sediment deposition, providing for water storage and nutrient cycling, and the periodic disturbance required by streamside plant communities.

Soil moisture regimes and water table fluctuations are often strongly tied to streamflow fluctuations, especially in alluvial valleys where surface water is often hydraulically connected to shallow groundwater in the floodplain aquifer (Castro and Hornberger 1991; Busch et al. 1992). In some cases, groundwater may sustain streamside vegetation by tapping groundwater sources. However, high temporal and spatial variability in stream-groundwater interactions are common.

The dependence of streamside vegetation on instream flows rather than groundwater may be intermittent rather than continuous along a stream. Water entering floodplain aquifers from direct precipitation, colluvial aquifers, up-gradient valley aquifers, fault leakage, or other geological features may be locally more important than water from the channel in supporting streamside vegetation. In arid environments, the association between riparian vegetation and streamflows is particularly evident (Stromberg and Patten 1996). Because of the complexity of factors, site-specific data (observations of water table elevations and stream stage over time) are needed to determine the nature of the dependence of alluvial water tables upon streamflow (Harris et al. 1987).

Year-round baseflows may be needed in some situations to maintain streamside vegetation, but baseflow has a minor direct role in maintaining the physical character of the channel. For example, vegetation along streams in steep alpine environments is less dependent on instream baseflow because lateral inflow from hillslopes supplies adequate moisture to the rooting zone (Stromberg and Patten 1996). In many high elevation or humid regions typical of National Forests, the prevailing

Summary of the Scientific Basis for Channel Maintenance Streamside Vegetation Flows:

- The flow regime, including magnitude, duration, timing, and frequency of flow, has a profound effect on streamside vegetation.
- Changes to streamside vegetation at the boundary of the channel have the most impact on stream bank stability and maintaining the channel.
- Flows above bankfull help to scour vegetation from the channel and provide for periodic floodplain disturbance and groundwater recharge that many species require for regeneration.
- Seasonal groundwater levels and the ability of roots to access soil moisture often sustain streamside vegetation without the need for in-channel flow. Therefore, periodic overbank flows are often adequate to meet streamside vegetation needs for regeneration.
- Year-round baseflows may be needed to sustain protective streambank and floodplain vegetation in some situations, typically losing reaches in arid and semi-arid regions.
- Because of the complexity of streamflow, water table, and soil moisture interactions, and their relation to the needs of riparian species, site-specific analysis is required to estimate maintenance flows needed to sustain riparian vegetation.

climatic regime is moist enough to sustain vegetation. Also, return flows and tributary inflows below irrigation diversions may replenish groundwater and soil moisture sufficiently to maintain vegetation. Furthermore, in many situations where fisheries instream flows are provided, these baseflows are adequate to sustain riparian vegetation communities during low flow periods.

Reaches that lose water to the subsurface, in wide, lowland, unconfined valleys in arid and semi-arid regions are most likely to require a seasonal baseflow to maintain the water table and dependent riparian vegetation. In contrast, streamside vegetation along upland streams containing reaches that seasonally gain water from subsurface flow can typically be sustained without in-channel flows that supplement the high flows required for sediment transport. These gaining streams are typically found in humid regions and mountain canyons that often have adequate year-round soil moisture and subsurface input from hillslopes. Site-specific investigation will be required to define the nature of stream-subsurface flow connectivity and the seasonal needs for flows to maintain vegetation. A good guideline for maintaining riparian vegetation in a natural state is to preserve the natural phases of the annual hydrograph to the extent feasible (Poff et al. 1997).

Adverse Effects of a Lack of Channel-Maintaining Flows

Streams need to retain essential channel maintenance instream flows that convey sediment because future off-stream diversions for uses such as irrigation and municipal water supply may deplete critical portions of these flows. In the absence of these essential instream flows, sediment may accumulate in the channel and the channel may respond by altering its size, morphology, meander pattern, rate of migration, streambed elevation, bed-material composition, floodplain morphology, and/or streamside vegetation. These channel alterations are frequently detrimental to favorable flow and sediment conveyance.

The response of fluvial systems to river regulation has been well documented (Schumm 1971; Bray and Kellerhalls 1979; Petts 1980; Williams and Wolman 1984; Andrews 1986). Most of these studies are based on the morphological effects of dams on large river systems with low gradient channels. Typical responses to reduced flows include a decrease in channel size and capacity, aggradation at the confluence of tributaries, an increase in riparian vegetation, and narrowing of the channel with effects often extending far downstream. Reduced channel capacity, through narrowing of channel width, is the most common adjustment to flow depletion.

Flows from headwater streams commonly found on National Forest System lands are generally reduced by irrigation diversions rather than dams. Dams affect sediment and flow regimes differently than irrigation diversions. Thus, study results downstream of large dams are difficult to extrapolate directly to diversions. Large dams typically trap all bedload sediment, dramatically reduce flood peaks, and often increase low flows while keeping annual water volumes unchanged. In contrast, diversions are typically low-head structures that reduce the magnitude and duration of flows during a part of the year (typically the growing season), have minor effects on intermediate and large flood peaks, and are generally designed to trap or divert a small proportion of total annual bedload.

Channel Response Below Diversions

The extent of channel alteration from small-scale irrigation diversions is incompletely understood. Channel response is complex and depends on the amount of water diverted (flow volume); changes in flow rates and flow duration; physical characteristics of the channel below the diversion with respect to bed mobility thresholds and bank materials; timing, amount, and size of sediment supplied to the channel as well as that removed by the diversion structure; the length of time the diversion has been in place; and the presence and species composition of riparian vegetation within the downstream channel. Because of this complexity, extrapolation of diversion studies requires caution.

Few researchers have studied channel response to diversion in small, mountainous watersheds. Wesche (1991) studied 20 channels in southern Wyoming and northern Colorado. Flow depletion ranged from 17 to 90 percent and had been going on from 12 to 106 years. Comparison of channel properties above and below diversions showed that in low gradient channels (less than 1.5 percent slope), streams narrowed, vegetation encroached, and flood conveyance capacity diminished. Changes to steep gradient channels (slopes greater than 4 percent) and moderate gradient channels (slopes 1.5 to 4 percent), however, lacked statistically significant change. Wesche concluded that high elevation, steep gradient channels with high stream energy, low sediment loadings, and short growing seasons can better maintain channel dimensions with reduced flow regimes over long periods of time than low gradient reaches.

Bohn and King (2000) studied 21 small diversion sites in Idaho. Although hydrologic records were unavailable at these sites, small diversion structures apparently failed to divert a significant portion of high springtime peak flows—implying that channel-forming flows passed down the channels. Estimates of edge-of-vegetation flow conveyance below diversions were significantly smaller than those above headgates by about 25 to 30 percent, indicating that flow reduction due to small diversions leaves discernable indicators in the channel.

Another study on several subalpine coarse-grained channels in the Rocky Mountains in Colorado was unable to detect significant changes in channel capacity between diverted and undiverted reaches and attributed this to the stability of subalpine channels and the large variance in channel dimensions (Ryan 1994; Ryan 1997). Total annual discharge had been reduced between 20 and 60 percent. The percentage of water diverted varied annually; however, the magnitude and frequency of bankfull and higher flows remained nearly the same. Observed reductions in channel width, where they occurred, were due to vegetation establishment on formerly active surfaces. Width reduction ranged from 35 to 50 percent but was limited to low gradient (1 to 2 percent slopes) and pool-riffle channels with gravel bars. Step-pool channels, dominated by large boulders with slopes greater than 3 to 4 percent, lacked evidence of notable decline in their width—supporting the conclusions of Wesche (1991).

Because of the systematic, long-term nature of flow diversions, long-term effects are probable. Centuries may be needed, however, to detect significant reductions in flow capacity in steep gradient channels (Ryan 1994). While some flows are needed in all channels to maintain proper function, adverse effects are most easily detected and more likely to occur in low gradient, self-formed alluvial channels.

Quantification Approach

At the simplest level of abstraction, a regime of natural flows is essential for the maintenance of natural stream channels. This flow regime must provide for sediment transport of the particles supplied to the channel and making up the bed of the channel and provide for streamside vegetation to protect and bind the channel banks. In fulfilling these roles, sediment and vegetation have both separate and combined influences on channel maintenance processes.

The proposed channel maintenance approach therefore consists of **bedload sediment transporting flows and streamside vegetation sustaining flows**. Flows to transport bedload sediment are a critical part of every channel maintenance instream flow. Intermediate to high sediment transporting flows provide some benefits to vegetation and may be adequate to sustain streamside vegetation in many geographic circumstances where adequate moisture from non-stream sources is available year round. In other situations, flows to sustain streamside vegetation will need to be evaluated on a site specific basis.

Typical Channel Maintenance Hydrographs

This section provides an overview of typical channel maintenance hydrographs using data in a hypothetical example from Halfmoon Creek, a snowmelt-dominated gravel-bed stream located in Colorado. This section is intended to help the reader understand the nature of a channel maintenance instream flow regime, including the lower and the upper limit of the claimed flows and the amounts of water typically required for channel maintenance from wet through dry years. Procedures and data needed to estimate the lower and upper limits are explained in a subsequent section.

A typical sediment-transporting channel maintenance hydrograph includes a range of discharges making up a portion of the rising and falling limbs of the annual hydrograph, excluding discharges in excess of the 25-year event. Conceptually, the required maintenance flow regime begins at a discharge at which transport-limited gravels making up the bed of the channel begin to move ($Q_{trigger}$) and includes all flows up to and including the instantaneous 25-year flow (Q_{cap}). This range of flows moves all bedload sediment, scours vegetation from the channel, partially inundates the floodplain, and provides high flow functions needed to sustain streamside vegetation. These essential channel maintenance flows are claimed for the entire duration during which they naturally occur. Figures 2a, b, and c show examples of typical hydrographs for maintaining bedload sediment transporting at Halfmoon Creek, Colorado, for average, high, and low runoff years, respectively using an average lower limit flow initiation value.

The channel maintenance flow regime in the example was specifically selected to begin at 0.8 of bankfull discharge to illustrate the effect on flow volumes derived from using an average lower limit value.

Regardless of flow ignition values, most of the water required for channel maintenance occurs during high runoff years (figure 2b). During typical low runoff years, none of the annual water yield is needed for channel maintenance because flows exceeding the 0.8 of bankfull initiation flow fail to occur in dry years (figure 2c).

The volume of water available to accomplish channel maintenance varies significantly from year to year, averaging about 16 percent of the annual water yield over the long-term for Halfmoon Creek, Colorado, and ranging from zero to 60 percent for individual years. Figure 3 illustrates this sequence of channel maintenance flow needs from wet to dry runoff years defined in terms of annual water yield exceedence. Since channel maintaining flows rely on flow near and above bankfull, a high portion of channel maintenance water needs are satisfied during wet years. For example, in the highest flow year (exceeded 5 percent of years, 1984) 46 percent of the annual water yield is used for channel maintenance while during progressively lower runoff years smaller portions of the annual yield are used for channel maintenance. In an average runoff year (exceeded 50 percent of years, 1972) only 19 percent of the yield is used for channel maintenance. During nearly one-third of the low flow years, channel maintenance flows are unnecessary because gravel-transporting discharges are seldom achieved. The decreasing pattern of water used for channel maintenance progressing from wet to dry years is illustrated in figure 3. While this is one example from Colorado, other streams follow the same general pattern.

The selection of the lower limit flow initiation value influences both the volume of water needed for channel maintenance and the number of years that flows exceeding the threshold occur. As discussed previously, Phase 2 transport flow initiation typically begins at discharges between 60 to 100 percent of bankfull discharge. For the Halfmoon Creek example, a lower flow initiation value of 0.6 of bankfull increases the average volume needed for channel maintenance to 22 percent of annual water yield with a range of zero to 75 percent for individual years. During nearly one-quarter of the low flow years, channel maintenance flows would be unnecessary because gravel-transporting discharges exceeding 0.6 of bankfull fail to occur. In contrast, a higher flow initiation value set at bankfull discharge decreases the average volume needed for channel maintenance to 7 percent of annual water yield with a range of zero to 47 percent for individual years. During almost 60 percent of the years, flows exceeding bankfull would fail to occur and no water would be needed to satisfy channel maintenance purposes.

Additional streamside vegetation flows may be required to supplement the bedload transporting flows in some circumstances. These additional baseflows or recession flows may be necessary to prevent vegetation establishment in the channel or to provide for streamside vegetation maintenance and regeneration.

Quantifying Flows Needed for Sediment Transport

The bedload sediment transporting flows are primarily designed to route the total mass and sizes of alluvial bedload supplied to the channel through the channel system in order to maintain channel capacity with the minimum amount of water. This requires defining the beginning of Phase 2 sediment transport (lower limit) that dominates channel morphology and function and some high flow (upper limit) above which undesirable flooding may occur and which fails to transport significant amounts of sediment.

Estimating the Lower Limit of Sediment Transporting Flows

Conceptual Basis of the Lower Limit

The onset of measurable bedload transport happens over a narrow range of discharges and is thus practically and conceptually initiated by a threshold discharge. Because of the heterogeneous particle size distribution of the channel-bed surface in gravel-bed rivers, finer particles are initially mobilized by low flows. These often supply-limited fine particle sizes mobilize earlier than the transport-limited larger sizes. Therefore, as flows rise, sand and finer gravels on the channel-bed surface mobilize first (Phase 1 Transport) followed by the transport of coarser particles (Phase 2 Transport).

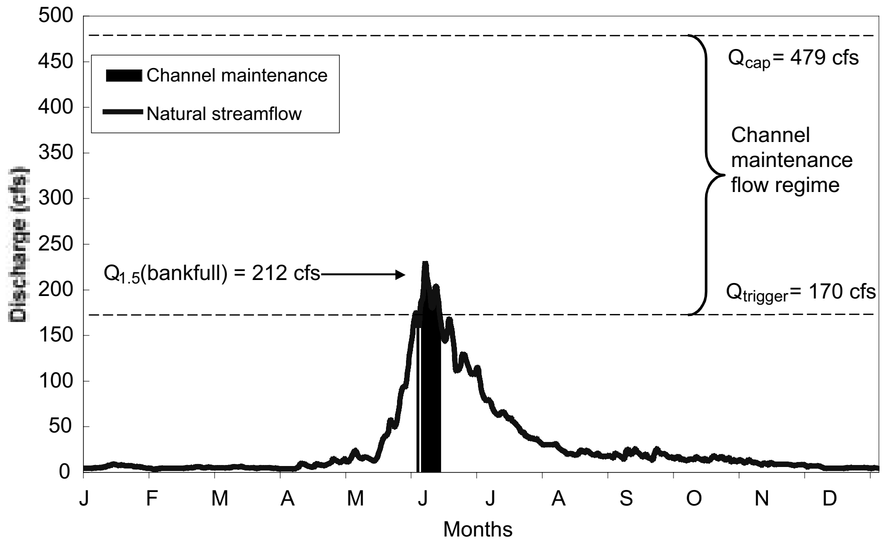

Figure 2a—A typical channel maintenance flow hydrograph applied to an average runoff year (exceeded 50% of years). The discharge data is from Halfmoon Creek, Colorado in 1972. The lower limit ($Q_{trigger}$) used to initiate the channel maintenance flow regime is 0.8 of the 1.5-year flow and the upper limit (Q_{cap}) is the 25-year flow. For the average year shown, channel maintenance flows require 3,851 acre-feet of water of the 20,023 acre-feet of total natural water yield, or 19% of the annual flow in

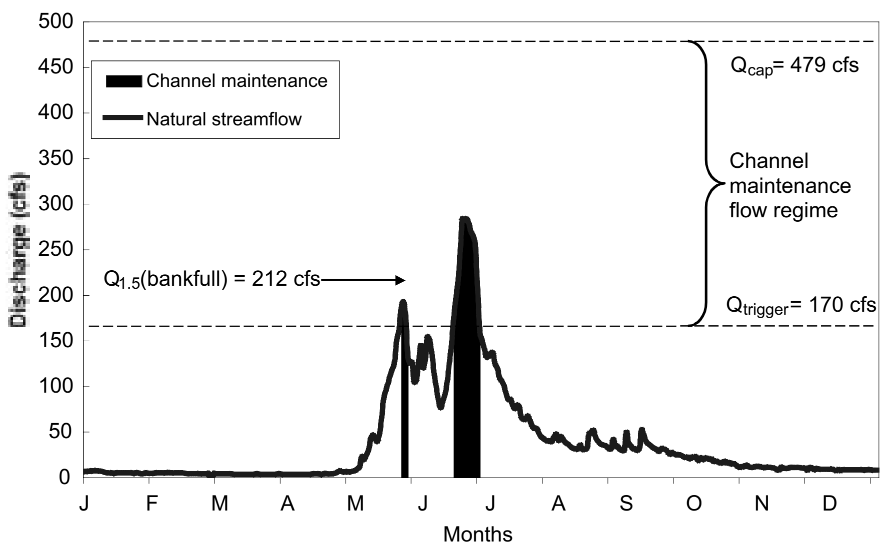

Figure 2b—A typical channel maintenance flow hydrograph applied to a high runoff year (exceeded 20% of years). The discharge data is from Halfmoon Creek, Colorado in 1970. The lower limit ($Q_{trigger}$) used to initiate the channel maintenance flow regime is 0.8 of the 1.5-year flow and the upper limit (Q_{cap}) is the 25-year flow. For the high runoff year shown, channel maintenance flows require 6,938 acre-feet of water of the 27,070 acre-feet of total natural water yield, or 26% of the annual flow in this year. Most of the channel maintenance work takes place during these high runoff years.

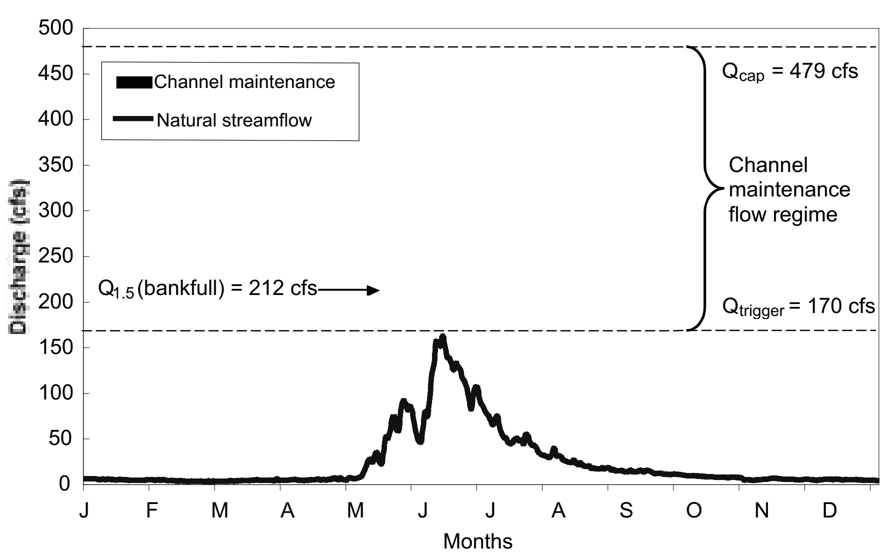

Figure 2c—A typical channel maintenance flow hydrograph applied to a low runoff year (exceeded 80% of years). The discharge data is from Halfmoon Creek, Colorado in1991. The lower limit ($Q_{trigger}$) used to initiate the channel maintenance flow regime is 0.8 of the 1.5-year flow and the upper limit (Q_{cap}) is the 25-year flow. No channel-maintaining sediment transport occurs during this dry year because low flows are unable to move coarse sediment. During the low runoff year shown, none of the 16,094 acre-feet of total natural water yield is needed for channel maintenance.

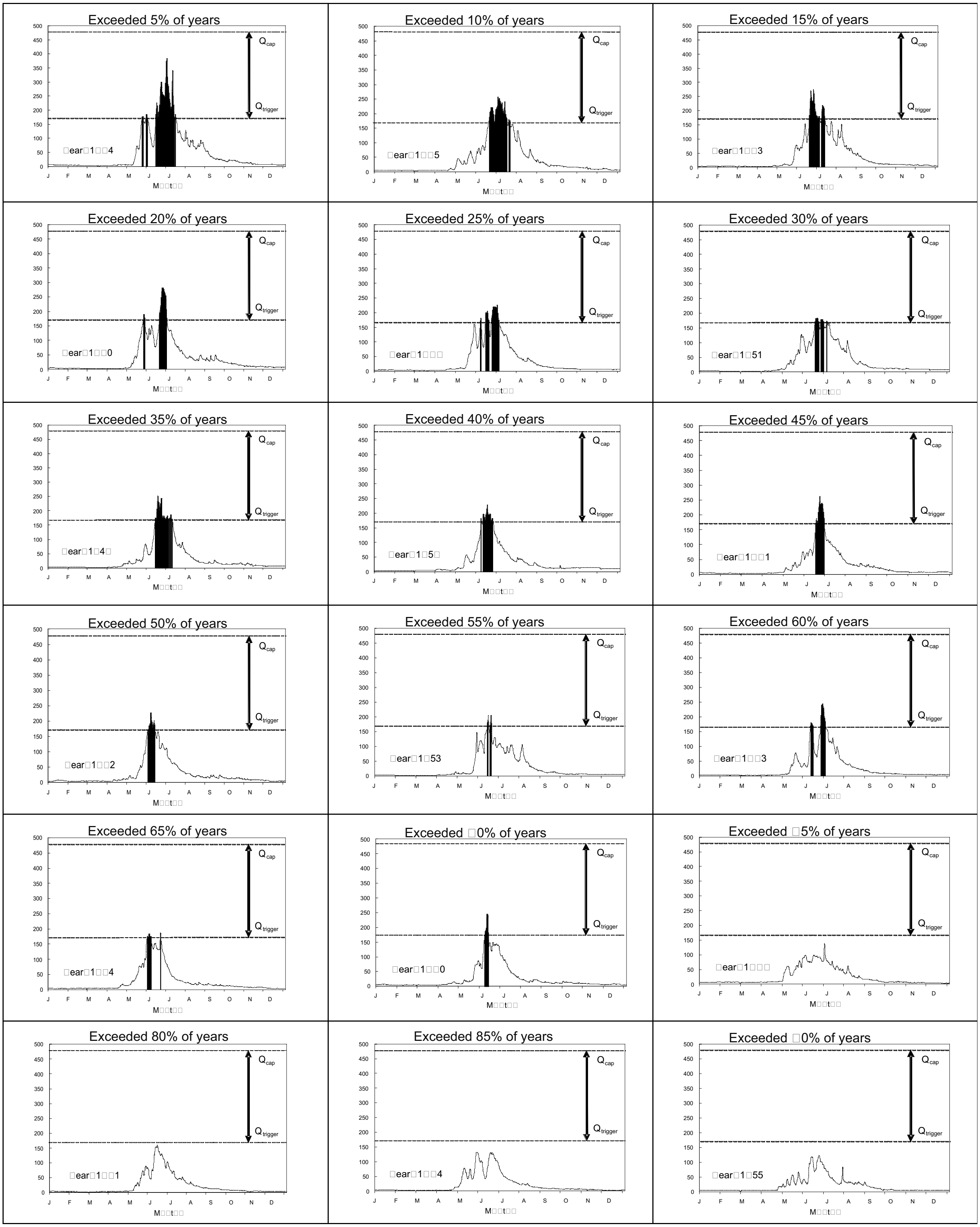

Figure 3—A sequence of channel maintenance flows from wet (exceeded 5% of years) to dry (exceeded 90% of years) years. The volume of water needed for channel maintenance (shown in black in the figures) is highly variable from year to year and the percent of annual water yield used for channel maintenance decreases from wet to dry years in a regular manner. During many low flow years (about one-third of all the years), channel maintenance flows are unnecessary because gravel-moving discharges fail to occur.

In gravel-bed rivers, the channel-bed is commonly coarser than the subsurface (Church et al. 1987; Dietrich et al. 1989). This relatively coarse surface layer limits entrainment and transport of finer subsurface particles until discharge is sufficiently great to mobilize the coarser surface layer (not just moving sand size particles over an immobile bed as in Phase 1 Transport) making the finer subsurface bed material also available for transport. The discharge necessary to begin to mobilize the coarse surface layer is the threshold discharge for Phase 2 Transport.

A general long-term bedload transport model that incorporates these transport initiation concepts within the context of magnitude-frequency analysis (figure 4) serves as the template for estimating the specific range of natural flows necessary for channel maintenance. The threshold concepts of Phase 1 Transport ($Q_{threshold}$) and Phase 2 Transport ($Q_{trigger}$) are used to estimate the starting point of the channel maintenance flow regime.

Total bedload transport in figure 4 is computed as the long-term product of flow frequency (days) and bedload transport rate (tons/day) as proposed by the magnitude-frequency concept of Wolman and Miller (1960). The area under the total bedload transport curve represents 100 percent of the bedload transport. We hypothesize that all discharges greater than the threshold discharge for bedload transport ($Q_{trigger}$) will move bedload in its entirety because these streams are supply limited, meaning that the streams can move more sediment, especially in the finer classes, than they presently do.

To estimate long-term total bedload transport, the following data and analyses are required: (1) historical daily mean discharge to estimate flow frequency and amount; (2) a bedload transport rating curve derived from measured bedload sampling; and (3) total bedload transport computed by combining daily mean discharge and bedload transport rate over a long-term flow record. Typically, existing or synthesized flow records of 20 years or longer adequately represent the long-term with respect to discharge. Bedload measurements made over a full range of flows including those exceeding bankfull stage adequately represent long-term sediment transport provided the channel is in quasi-equilibrium and lacks substantial sediment pulses or waves that may change the transport curve.

The model illustrates that low flows, even though they occur most of the time, transport relatively minor amounts of bedload sediment because the bedload transport rate is near zero. In contrast, higher flows become more efficient at transporting bedload (figure 4). For example, doubling the flow rate more than doubles the bedload transport rate. Very large flood flows, although having the highest transport rates, account for relatively minor amounts of bedload sediment because high flows occur infrequently and are generally of short duration. Consequently, the largest proportion of the total bedload is transported by flows around the peak of the total bedload transport curve (i.e., the effective discharge). In many gravel-bed rivers, bankfull discharge approximates effective discharge.

Channel maintenance instream flows reserve the highest flows (those most efficient at transporting bedload sediment) and then progressively include lower flows. This assures transport of the highest percentage of total bedload mass with the least volume of water.

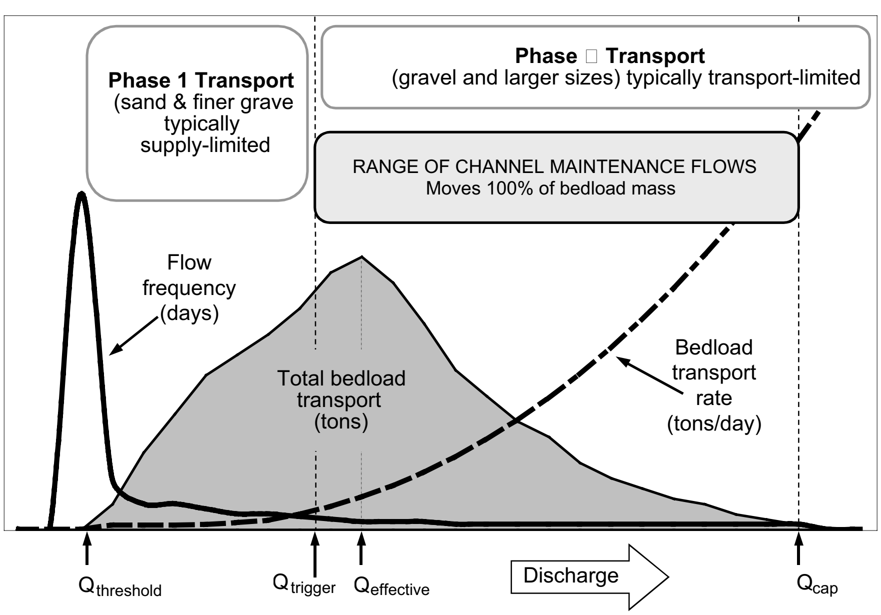

Figure 4—Schematic of long-term total bedload transport model for gravel-bed rivers based on Wolman and Miller's magnitude-frequency concepts. Bedload movement begins at $Q_{threshold}$, flows between $Q_{threshold}$ and $Q_{trigger}$ are Phase 1 transport, $Q_{trigger}$ is the beginning of Phase 2 transport, flows exceeding $Q_{trigger}$ are Phase 2 and move the majority of the coarse sizes, and Q_{cap} is the upper limit of the required channel maintenance flow regime. Flows from $Q_{trigger}$ to Q_{cap} constitute the range of flows necessary to maintain the channel.

The total bedload transport model (figure 4) implies that all flows greater than $Q_{threshold}$ are needed to transport 100 percent of the total bedload mass. However, due to the supply-limited nature of gravel-bed rivers, meaning that the streams are capable of moving more sediment than they presently carry, a narrower range of high flow, beginning at $Q_{trigger}$, can still move almost 100 percent of the bedload sediment over the long-term without compromising channel maintenance objectives (Wolman et al. 1997). While some temporary increase in fine sand content may occur in the channel due to loss of some of the natural hydrograph (Parker et al. 2003), the deviation of the proposed channel maintenance hydrograph from the natural hydrograph is small and the temporary increase in surface fines is judged to be insignificant to channel processes.

While a temporary deposition of fines is generally undesirable for ecological reasons, we hypothesize that the accumulated fines will be moved by larger flows with excess stream energy that occur later in the year or in subsequent years. Improved efficiency of gravel transport occurs because the rate of gravel transport has been shown to increase with increasing sand content (Wilcock 1998). Wilcock demonstrated that an increase in sand content of approximately 15 to 30 percent increases the efficiency with which the stream transports gravel-sized material. Shifting channel maintenance flows from the onset of sand and finer gravel movement ($Q_{threshold}$) to the onset of medium gravel movement ($Q_{trigger}$), thus delaying the initiation point of the channel maintenance hydrograph, is desirable because it minimizes the long-term volume of water needed for channel maintenance.

Phase 1 flows between the onset of sand movement and gravel movement can only be given up without sacrificing the aim of channel maintenance flows when streams are armored and the sand and fine gravel are supply-limited. In streams with abundant supply of all grain sizes (e.g., transport-limited streams, such as sand-bed streams), flow is transporting bedload at or near its capacity most of the time. In these instances, all flows capable of transporting bedload are essential to assure conveying all of the bedload, and claimed channel maintenance flows may need to start with the critical conditions for sand ($Q_{threshold}$). Direct bedload measurements or an analysis of bed mobility may be required in some circumstances to determine the applicability of the model proposed here for channels impacted by excessive fine sediment such that the channel is out of equilibrium.

The discharge associated with the "threshold" shift from Phase 1 Transport to Phase 2 Transport has been estimated from size analysis of measured bedload samples (Ryan et al. 2002; Emmett 1999), from measured bedload samples from in-channel sediment traps (Bunte et al. 2001), or from analysis of bed material composition (McNamara et al. 2000). Discharges sufficient to move the coarse surface layer typically occur only during a small percentage of the time. Obtaining sufficient bedload measurements to detect the threshold flow is a difficult task requiring a large number of well-timed samples. Site-specific measured data is always preferred, but may be infeasible. In these cases, it may be appropriate to extrapolate values of trigger flows from published literature (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker 1997; Ryan et al. 2002; Trush et al. 2000; Ryan et al., submitted) and verify these with measurements at local sites.

Methodology for Estimating the Lower Limit

Precise estimation of the lower limit starting point of the channel maintenance flow regime is challenging. While the existence of different phases of transport in gravel-bed rivers is widely acknowledged, the threshold between phases often lacks a precise value due to the nature of bedload transport phenomena and sampling difficulties. All estimations require some degree of professional judgment applied to the data available.

The starting point is best estimated from a combination of considering the particle size distributions of the bedload, the size distribution of the bed material, and bedload transport rates. In our judgment, the starting point of the required flows for channel maintenance is best estimated by examining direct empirical bedload measurements. Direct measurement provides tangible evidence of the particle sizes and the amount of material moving at different discharges without reliance on computational techniques or theoretical constructs of sediment transport. Indirect extrapolation approaches based on research studies may be necessary where data are unavailable.

Direct Approaches

The following direct approaches using measured bedload data may be used to estimate the starting point of channel maintenance flows. Measured bedload data can be obtained using either Helley-Smith samplers or bedload traps (Bunte et al. 2001). The starting point can be inferred using visual estimation or the more rigorous piece-wise regression analysis, which also provides confidence limits on the estimate.

(1) Visual Estimation

Data from Little Granite Creek in Wyoming are used to illustrate visual estimation. Figure 5 shows bedload discharge plotted as a function of water discharge for Little Granite Creek in Wyoming using logarithmic scales commonly used to plot bedload rating curves (Emmett 1999). A logarithmic plot of bedload transport, however, obscures the sudden increase in transport rates associated with the starting point of channel maintenance. The data in figure 5 are plotted arithmetically by particle-size class in figure 6 (Ryan and Emmett 2002) to show a dramatic increase in bedload transport at about 220 cfs.

Dramatic, well-defined shifts as seen in figure 6 are seldom evident in bedload transport data sets. Visual identification of the starting point by its nature tends to be subjective. To minimize this subjectivity, collect sufficient bedload samples such that when the data are arranged by particle size class, at least 50–100 data points constitute the transport rate data on the graph. Make sure that the plot includes a large number of samples, well-distributed over the range of flows, and that it includes flows near bankfull discharge and higher. To aid visual estimation, look for abrupt increases in both the size and amount of material being moved in the range of 0.6 - 1.0 bankfull discharge, which has been shown to represent the onset of Phase 2 Transport. For Little Granite Creek, it is apparent that both the sizes and amount of bedload discharge increase dramatically at about 220 cfs, 96 percent of the field determined bankfull discharge of 230 cfs, suggesting a shift from Phase 1 Transport to Phase 2 Transport.

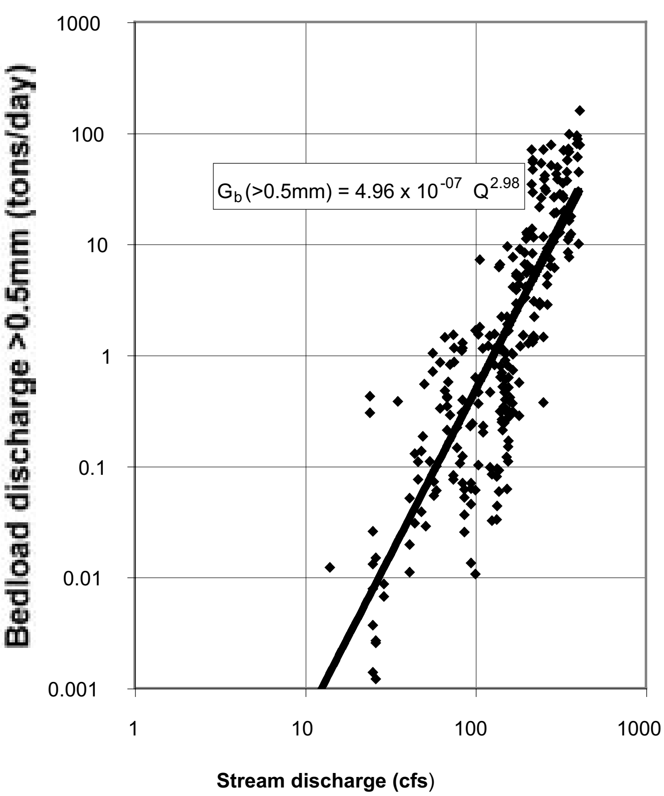

Figure 5—Logarithmic plot of bedload transport (G_b) as a function of water discharge (Q) for Little Granite Creek (from Emmett 1999). A logarithmic plot of bedload transport tends to obscure the sudden increase in transport rates associated with the starting point of channel maintenance.

(2) Piecewise Regression

To overcome the subjectivity and limitation of visual estimation, Ryan et al. (2002) apply a piecewise linear regression model to total bedload transport data. Piecewise linear regression fits one or more linear functions to ranges of data (Neter et al. 1989). Ryan et al. (2002) hypothesize the existence of different linear relationships for bedload transport over different ranges of discharge. One linear function is fitted to predominately sand-sized material representative of Phase 1 Transport, while a second linear function is fitted to higher flows representative of Phase 2 Transport that include coarser materials. The model is written so that the function is continuous at all points, including the breakpoint. The inflection point, where the fitted functions intersect, is termed the "breakpoint" and is interpreted to represent the flow at which a substantial change in the rate and nature of coarse-grained transport occurs (figure 7). The breakpoint generated by the piecewise linear regression model provides a statistically based, objective way of estimating the channel maintenance starting point.

The visual estimation and piecewise regression methods may produce different results, but in other analyses, they are quite similar (Ryan et al. 2002). Because breakpoint analysis fits a line that must have a slope for the upper portion of the data associated with coarser material, breakpoint analysis typically results in a starting point discharge lower than would be selected visually. For Little Granite Creek, Emmett using visual indicators, identified the starting point at about 220 cfs while breakpoint analysis estimates the starting point at 171 cfs (Ryan and Emmett 2002). Both estimates are within the confidence limits of the piecewise regression breakpoint analysis and suggest that Phase 2 transport begins as flows approach bankfull discharge.

While piecewise regression provides an objective, statistical procedure for estimating the threshold discharge, judgment is still essential to properly interpret the data. A robust analysis requires a high number of well-distributed data points spaced over a wide range of flows, including bankfull or greater discharges. Data gaps over the range of flows need to be avoided, particularly near the breakpoint. A minimum number of about 80 bedload

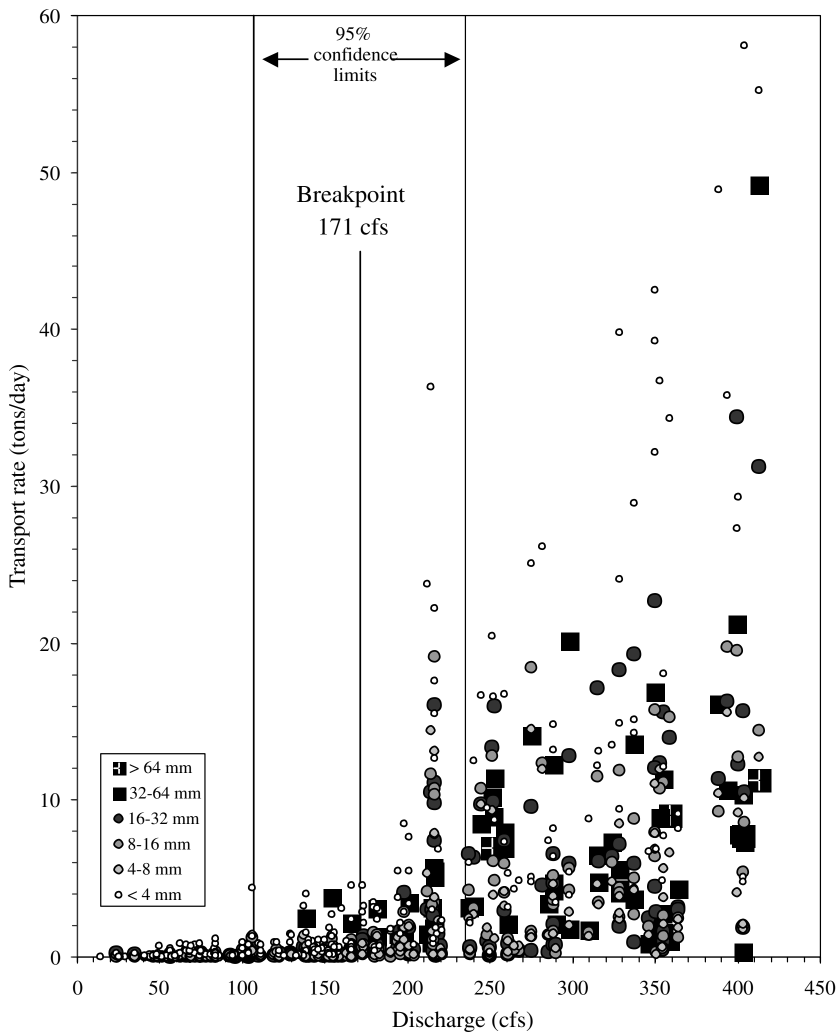

Figure 6—Arithmetic plot of bedload discharge and water discharge by particle-size classes for Little Granite Creek (from Ryan and Emmett 2002). Lines indicate values of the breakpoint discharge (171 cfs) and the 95% confidence limits on the breakpoint estimate. The discharge at which coarse gravel begins to appear in the samples coincides more or less with the value of the breakpoint. The rate of bedload transport increases dramatically at about 220 cfs -- a value within the confidence limits of the breakpoint estimate from the piecewise regression procedure. Both estimates indicate a substantial increase in the amount of bedload transport at flows approaching bankfull (230 cfs).

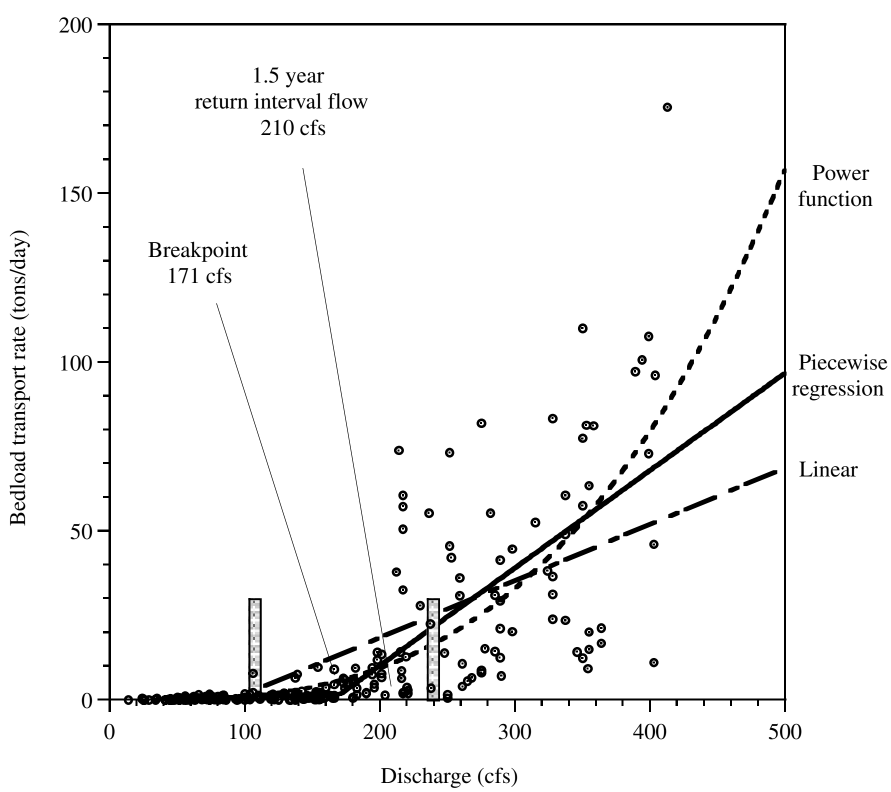

Figure 7—Arithmetic plot of total bedload transport and water discharge for Little Granite Creek (from Ryan and Emmett 2002). The figure illustrates three fits (linear, power, and piecewise linear) to total bedload transport data on arithmetic scale and shows the breakpoint of 171 cfs. Bars represent the 95% confidence limits on the estimate of the breakpoint; bar height is arbitrary.

transport samples are generally thought necessary for a robust analysis. A minimum of about 30 points is needed to estimate each of the piecewise regression functions. Conclusions drawn from smaller samples are difficult to interpret and typically have broader confidence interval bands (Personal communication, S. Ryan, 2003, Rocky Mountain Research Station).

Indirect Approaches

Channel maintenance flow quantifications may need to be quantified without benefit of detailed field data. In these instances, it may be necessary to rely on existing research studies (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker 1997; Ryan et al. 2002; Trush et al. 2000; Ryan et al. submitted) and extrapolate basic concepts regarding the starting point.

Sufficient research information exists at this time for selected regions to predict a starting point for broad-scale application. For example, studies by Ryan et al. (2002, submitted) of coarse-grained channels in Colorado and Wyoming concluded that the transition from Phase 1 Transport to Phase 2 Transport occurs between 60 to 100 percent of the 1.5-year discharge, with an average of 80 percent. An average starting point of 80 percent of the 1.5-year discharge provides a good first approximation for general application while a selection of 60 percent of bankfull provides a more conservative estimate for more mobile systems with higher sand loads. A limited number of sites should be measured in the geographic area of interest to verify that the selected starting point applies locally.

Estimating the Upper Limit of Sediment Transporting Flows

Conceptual Basis for the Upper Limit

Prevention of flood damage was a primary reason why Congress wanted "favorable conditions of water flows" from the National Forests. Numerous government agencies actively work to protect the public from the adverse impacts of catastrophic flooding, such as 100-year flood events, through regulations prohibiting occupancy of floodplains, flood insurance and flood control programs, and structural flood protection and floodproofing. Society generally considers property damage-causing flows as undesirable or "unfavorable." Therefore, as a practical matter, we propose placing an upper limit (Q_{cap}) on channel maintenance instream flows.

A 25-year flow upper cap for channel maintenance instream flows balances the need to limit flood damage while still transporting sufficient sediment, particularly the larger sizes, to fulfill channel maintenance and riparian regeneration functions. Because the 25-year event is equaled or exceeded infrequently, on average in 4 percent of years, flows in excess of the 25-year event transport relatively small amounts of sediment over the long term. Cumulative sediment transport computations of long-term flow records in Idaho and Colorado indicate that flows exceeding the 25-year flow generally transport about 1 percent or less of total bedload (King 1998; Schmidt 1998). This amount of forgone sediment transport will likely have an insignificant impact on channel capacity. Our analyses of several sites in Colorado indicate that limiting flows to the 5-year event risks leaving almost 10 percent of the sediment in the channel.

Rare, extremely high flows are part of the natural flow regime and have geomorphic and ecological importance over extended time scales (Junk et al. 1989). Scientific literature suggests that intermediate flows primarily affect channels and the floodplain, while large hydrologic events increasingly affect broader landscape features including terraces and valley sides (Petts and Maddock 1996). Extreme high flows may excessively widen the channel, damage property, structures, aquatic and riparian resources, and even threaten lives. Extreme floods may have catastrophic impacts on some channels (Newson 1980; Stewart and LaMarche 1967) while leaving others virtually unchanged by dispersing flood water over the valley floodplain and terraces (Pitlick 1993; Miller 1990; Costa 1974). Most of the distinctive morphology of the valley bottom, especially in low-gradient alluvial streams, is from gradual reworking of fluvial sediments by intermediate flows whereas in low order tributary mountain streams, bedrock control, hillslope process, tributary input, and extreme high flows take a more dominant role (Grant and Swanson 1995).

Hill et al. (1991) identify valley-forming flows as peak discharges that exceed the 25-year recurrence event. The ratios of average water depth at mean annual discharge divided by mean bankfull depth for flow events of various recurrence intervals for alluvial rivers in four regions of the United States show remarkable consistency (Leopold et al. 1964; Emmett 1975). For a 25-year event, the average flow depth is 1.5 times the bankfull depth and it ranges from 1.3 in Idaho to 1.7 in the Cascades. This implies that a 25-year flow typically inundates the floodplain to an average depth of about 1.5 times the mean bankfull depth. This depth of overbank flow periodically inundates, transports sediment, and creates new surfaces for streamside vegetation regeneration and floodplain maintenance.

With respect to vegetation, Hill et al. (1991) estimated that riparian maintenance flows (i.e., flows that inundate the riparian zone) occur at frequencies between 1.5 and 10 years. Trush et al. (2000) concluded that large flows, those generally exceeding 10- to 20-year recurrence intervals, are necessary to sustain floodplain morphology and complexity. These overbank flows reshape meander sequences, form and maintain side channels, avulse main stem channels, rejuvenate riparian stands, scour floodplains, and perpetuate off-channel wetlands. Based on this information, the 25-year event appears to be a conservative estimator of flows adequate to periodically inundate riparian vegetation and maintain floodplain complexity; accordingly, we chose to use it as a reasonable upper limit

Methodology for Estimating the Upper Limit

The upper limit of the channel maintenance instream flow is the 25-year instantaneous peak flow. It can be directly estimated using standard flood frequency analysis if streamflow data are available and the period of record is adequate (U.S. Water Resources Council 1982). Where flow data is lacking, regional flood frequency analyses techniques of the U.S. Geological Survey may be used (Jennings et al. 1994).

Deviation from the 25-year upper limit, that is, selecting a lower return period flood event, should only be done after careful consideration of the consequences of having a lower magnitude cap. Decreasing the upper flow limit increases the risk of sediment accumulation in the channel and may have other consequences of failing to maintain or regenerate riparian vegetation. Any downward adjustments should be supported by scientific study and analysis.

Quantifying Flows Needed for Streamside Vegetation

Streamside vegetation flows may be needed in addition to bedload sediment transporting flows to maintain vegetation and protect channel banks. Because bedload transporting flows exceed bankfull stage, they scour vegetation from the channel and periodically inundate, deposit sediment, and scour portions of the floodplain in snowmelt streams, often when viable seeds are being released, thus preventing germination on active bars. At the same time, overbank flows recharge local aquifers and provide disturbance to maintain and regenerate other vegetation communities. Generally, in temperate mountainous environments, adequate soil moisture during the growing season is available to sustain streamside and floodplain vegetation because subsurface flows contribute moisture to riparian soils, shallow groundwater aquifers recharge from overbank flows, and mountainous sideslopes contribute water to maintain soil moisture and baseflow.

A streamside vegetation flow component in addition to bedload transporting flows may need to be considered on a site specific basis. For example, specific baseflows for vegetation may be needed where riparian vegetation directly depends on year-long baseflows or groundwater derived from channel flows, or where significant growth of woody vegetation might occur in the channel without streamflow. Streamside vegetation maintenance flows may also include high flows for successful regeneration of a particular species (e.g., the recruitment box model for cottonwood regeneration) (Mahoney and Rood 1993).

An interdisciplinary team consisting of a riparian ecologist, hydrologist, and geomorphologist as a minimum is recommended to evaluate streamside vegetation flow needs and design site-specific studies to understand vegetation, streamflow, and groundwater interactions. Site-specific linkages between in-channel flow regimes and the maintenance requirements of streamside vegetation (Auble et al. 1994) need to be developed by the interdisciplinary team because universally applicable and generally accepted methods for estimating the flow regime necessary to maintain riparian vegetation and surrounding floodplains are presently lacking (Hill et al. 1991).

Analyzing and Displaying Results

This section provides guidance on analysis and display techniques that may be used to address questions such as:

- How much sediment is moved by the channel maintenance flow regime?
- What parts of the hydrograph move the most sediment?
- How efficient is the flow regime at moving sediment; that is, does the flow regime move the most sediment with the least water?
- Will flow fluctuations resulting from a channel maintenance claim adversely affect channel stability?
- How much water is needed for channel maintenance and how much remains for off-stream uses?
- How does the amount of water needed for channel maintenance vary from year to year?
- What geomorphic surfaces and vegetation are inundated by sediment transporting flows?

Cumulative Sediment Analysis

Cumulative sediment analysis provides one way to compute the total quantity of bedload sediment transported by the discharges in the channel. The results of the computation are used to show the amounts of sediment moved by various ranges of discharge (magnitude-frequency histogram) and the relationship between water, sediment, and the time required to move bedload sediment (cumulative sediment-water-time curve).

A cumulative sediment analysis requires a long-term flow record and a bedload rating curve. To do the cumulative sediment analysis, rank daily mean discharges for the period of record from low to high. For each mean daily discharge value, determine the frequency of that flow in days and then compute the cumulative frequency in percent. For each mean daily discharge value, determine the water volume in acre-feet and as a cumulative percentage. Assign a bedload transport rate in tons per day to each mean daily discharge from a bedload rating curve for the site. For each mean daily discharge value, compute total bedload in tons and as a cumulative percentage. A small portion of a sample computation is illustrated and explained in table 1.

The results of the computation are best examined graphically. Two types of data display are useful to understand sediment-discharge relationships: (1) Magnitude-Frequency Histograms, and (2) Cumulative Sediment-Water-Time Curves.

Magnitude-Frequency Histograms

The magnitude-frequency histogram (figure 8) shows the frequency of discharge and the total bedload transported by uniform increments of water discharge (cfs). The purpose of this analysis is to illustrate that over the long-term a majority of the bedload is typically moved by a range of intermediate discharges and that this range includes bankfull discharge.

To construct the histogram, select 20 to 30 equal interval discharge bins and sum the previously computed total bedload transport for each bin. Express bin totals as percentages and plot them versus discharge bin midpoints. Alternatively, magnitude-frequency histograms can also be developed by breaking a flow duration curve into 20 to 30 equal-interval discharge bins and applying

Table 1—Example cumulative sediment analysis worksheet illustrating how to compute the values in each of the columns.

(1) Discharge (cfs)	(2) Discharge frequency (days)	(3) Cumulative frequency (%)	(4) Water volume (acre-feet)	(5) Cumulative water volume (%)	(6) Bedload transport rate (tons/day)	(7) Total bedload (tons)	(8) Cumulative bedload (%)
2	0	0.0	0	0.0	0.000	0.00	0.00
3	42	0.5	250	0.0	0.000	0.01	0.00
4	48	1.1	381	0.1	0.001	0.03	0.00
5	125	2.6	1,239	0.2	0.001	0.1	0.00
6	302	6.2	3,593	0.5	0.001	0.4	0.01
7	237	9.0	3,290	0.8	0.002	0.5	0.01
8	512	15.1	8,122	1.6	0.003	1.4	0.02
9	481	20.8	8,584	2.4	0.004	1.7	0.04
10	549	27.3	10,887	3.4	0.005	2.5	0.06
11	418	32.3	9,118	4.3	0.006	2.3	0.08
12	356	36.5	8,471	5.1	0.007	2.4	0.11
13	192	38.8	4,950	5.6	0.008	1.5	0.12
14	333	42.8	9,245	6.4	0.009	3.2	0.15
15	180	44.9	5,354	7.0	0.011	2.0	0.17
etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.

Description of computations:

Column 1: Discharge (cubic feet per second). Daily mean discharge values sorted from low to high for each distinct discharge for the entire period of record.
Column 2: Frequency (days). The total number of days each discharge occurred.
Column 3: Cumulative frequency (percent). The cumulative number of days expressed as a percent of total days for the period of record.
Column 4: Water volume (acre-feet). Discharge (column 1) multiplied by days (column 2) multiplied by a 1.983 conversion factor (1 second-foot-day = 1.983 acre-feet).
Column 5: Cumulative water volume (percent). The cumulative water volume expressed as a percent of total water volume.
Column 6: Bedload transport rate (tons/day). Multiply each discharge by the bedload transport equation ($Q_s = f(Q_w)$) estimated for the stream. In this example, ($Q_s = 0.000028Q_w^{2.21}$); column 1 raised to the 2.21 power multiplied by 0.000028.
Column 7: Total bedload (tons). Tons per day of bedload (volumn 6) multiplied by the frequency or days (Column 2) that a specific discharge occurred during the period of record.
Column 8: Cumulative bedload (percent). The cumulative bedload tons expressed as a percent of total tons of bedload.

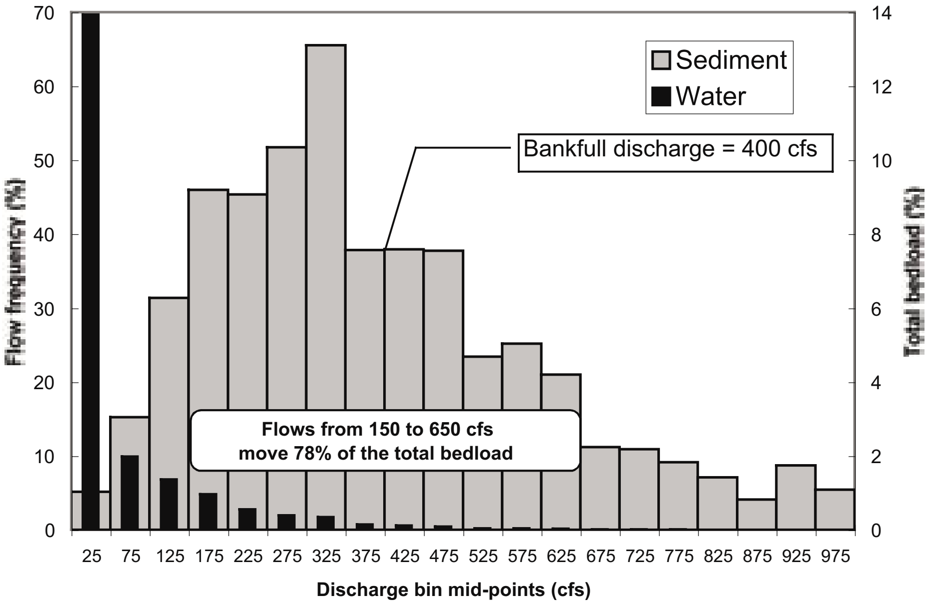

Figure 8—Example of a sediment magnitude-water frequency histogram. Much (78%) of the total bedload is transported by an intermediate range of flow between 150 and 650 cfs. Extreme high flows and the most frequent low flows tend to move a relatively small percentage of total bedload in the long-term compared to intermediate flows.

a bedload rating curve to discharge intervals to compute effective discharge and the magnitude-frequency histogram (Andrews 1980; Andrews and Nankervis 1995).

In this example (figure 8), 78 percent of total bedload is transported by the range of flow between 150 and 650 cubic feet per second, which encompasses bankfull discharge. Extreme high flows tend to move a relatively small percentage of total bedload compared to the amount of sediment moved by intermediate flows surrounding bankfull discharge. The most frequent flow bin (25 cfs) that occurs 70 percent of the time transports little sediment (1 percent). By contrast, the least frequent flow bin (975 cfs) occurs only 0.01 percent of the time and transports a similarly small amount (about 1 percent) of the sediment.

Cumulative Sediment-Water-Time Curves

A cumulative sediment, water, and time curve (figure 9) illustrates the relationship between bedload transport and the amount of water volume and time needed to accomplish the bedload transport. The curve displays the cumulative time, water, and sediment associated with various levels of discharge. The purpose of this analysis is to illustrate that all of the bedload can be moved with a relatively small portion of the annual water yield during a small part of the year. Data for the curves come from the cumulative sediment analysis.

Figure 9 illustrates an example channel maintenance flow regime starting at 260 cfs and going up to 1,000 cfs. The starting discharge (260 cfs) has been selected as described previously assuming supply-limitation of fines. The bedload making up 30 percent of the total is assumed to be Phase 1 fines that will be moved by flows of 260 cfs and higher. The upper limit is selected as the 25-year flow (1,000 cfs). This flow regime from 260 cfs to 1,000 cfs uses 35 percent of the water (100 percent minus 65 percent) and occurs on average 6 percent of the time (100 percent minus 94 percent). The remaining 65 percent of the water that occurs 94 percent of the time, 243 days of the year, is available for other purposes.

Analysis of Ramping Rates

The channel maintenance instream flow regime follows natural flow patterns between the upper and lower limits once the channel maintenance flow is initiated. Concern often arises that excessive ramping rates, that is, rapid increases in flow at the beginning of the channel maintenance hydrograph or rapid decreases in flow at the end of the required flows, may result in damage to the channel and aquatic species. Since channel maintenance flow regimes normally begin and end at discharges less than bankfull, a concern exists that rapid short-term flow increases or drawdown between baseflows and the starting point may adversely impact channel banks. The concern is greatest where the flow changes affect sparsely vegetated, steep, sandy or silty erosive banks, or clay banks that may slump due to water retention and the build-up of positive pore pressures during drawdown (Thorne and Tovey 1981; Springer et al. 1985). In addition, the change in stage over time is often perceived to be substantially greater than that experienced under unregulated conditions. Some of this perceived concern may result from vertically exaggerated cross-section

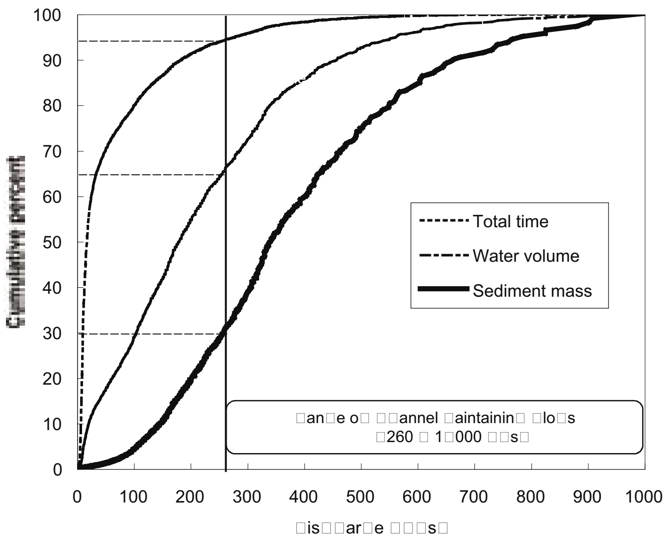

Figure 9—Cumulative sediment-water-time curves showing cumulative percents of sediment, water, and time for a channel maintenance regime from 260 to 1,000 cfs. The channel maintenance flow regime from 260 to 1,000 cfs uses 35% of the water (100% - 65%), and occurs on average 6% of the time (100% - 94%). The remaining 65% of the water occurs 94% of the time and is available for other purposes.

plots that suggest greater relative drawndown than what occurs naturally in channel systems.

In most gravel-bed rivers, the area of potential adverse impact due to rapid flow changes is the channel perimeter between the bottom of the channel (the stage of zero flow or low baseflows) and the stage of the starting point of the channel maintenance flow regime (normally a value around 0.8 bankfull discharge). This region is typically part of the channel bottom that slopes gently toward the stream banks, and for many gravel-bed rivers it is armored by coarse bed materials. Banks of gravel-bed rivers in the Interior West are frequently well vegetated and often composed of well drained non-cohesive gravel or coarser materials. The physical setting of gravel-bed rivers in this region therefore mitigates against much of the adverse channel damage that might result from rapid flow changes.

Several additional factors work to minimize adverse ramping effects due to the initiation of a channel maintenance flow regime. In most cases where irrigators manage water withdrawals, water is turned into the channel over a one day period of time, rather than as an instantaneous "wall of water." Typically, the channel maintenance hydrograph is triggered during the spring runoff when diversion is minimal, runoff is at a maximum, and a significant amount of natural runoff is already in the stream channel. In many instances, diverters either lack physical capacity or a water right to divert significant flow from the stream. In other cases, instream flow requirements for fisheries or other purposes may require leaving some water in the channel.

All of these factors work to reduce the stage difference between existing flows and the stage of the channel maintenance starting point discharge, reducing potential ramping impact. Flows above the starting point follow natural ramping rates and are therefore unaffected by the nature of the channel maintenance flow regime.

A stage-discharge relation for the cross-section where the analysis of ramping takes place can be used to evaluate ramping. One can examine the historical flow record, use channel cross-sections, and use a stage-discharge relationship to determine the maximum daily natural changes in stage and discharge and compare it to stage changes expected from implementing the instream flow regime. Direct the analysis toward the effect changes of stage have on banks and the channel rather than looking at changes in flow volumes or rates alone.

Fluctuations in stage from the proposed flow regime that exceed natural stage fluctuations indicate an area of concern. The degree of armoring of the channel, the nature of bank materials, vegetation rooting characteristics, and the elevation of side channels, if fisheries are a concern, may also be considered in an analysis of bank and channel resilience to the effects of ramping.

If the analysis indicates a need for gradual increases or decreases, it may be possible to negotiate acceptable rates of stage change and operating procedures with affected water users on a case-by-case basis. The goal of these negotiated agreements would be to turn water into and out of the channel gradually over several days. Arrangements of this sort may have benefits for water users because gradually turning water into irrigation conveyance facilities avoids damage. Giving up some water from the prescribed channel maintenance flow to achieve a mutually agreeable operating procedure may avoid undue complexity in the claim structure and may benefit both parties.

Long-Term Water Use Trends

Since the channel maintenance flow regime varies from year to year depending on flow conditions, a simple statement of the average percentage of the mean annual flow essential to satisfy instream flow needs is inadequate to properly characterize the nature of long-term water use. An analysis of the historical flow record is useful to gain insight into how much of the natural flow regime needs to remain in the stream for channel maintenance and how much is likely to be available for other off-stream uses.

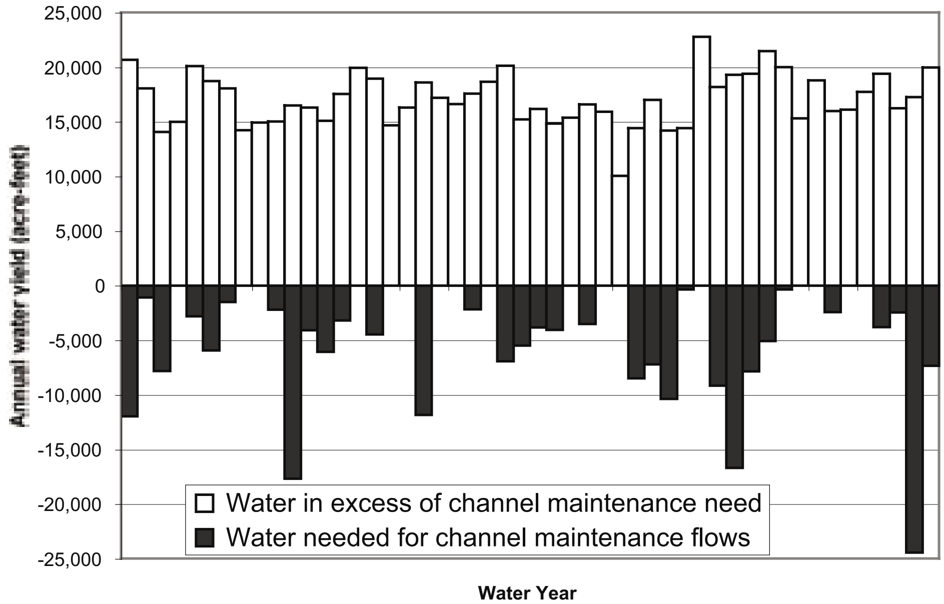

Figure 10—A display of the long-term partitioning of annual water yield between that needed for channel maintenance and that excess to channel maintenance needs. During some years, no water is needed for channel maintenance while a firm yield of about 15,000 acre-feet of water in excess to channel maintenance needs is annually available except for one drought when water yield is reduced to about 10,000 acre-feet.

The analysis can be conducted by obtaining a long-term historical flow record at or near the site, estimating the appropriate channel maintenance flow regime for the site, superimposing the channel maintenance flow regime on each year of the historical record, and tabulating the natural and instream flow water volumes for each year. Figure 10 displays the partitioning of total annual water yield between that required for channel maintenance and that available for others for Halfmoon Creek, CO, a stream with a 50-year period of record. During some years, no water is needed for channel maintenance while over 20,000 acre-feet are needed in other years. On average, about 17,100 acre-feet of water is available for other uses including fish habitat or other instream flow needs. In most years, a firm yield of about 15,000 acre-feet of water will be available and the excess is never less than 10,000 acre-feet.

The nature of the channel maintenance flow regime is such that in drought years significant water in excess of channel maintenance needs remains available for appropriation by water users. In fact, during the worst drought years, all the water is available because starting point flows for channel maintenance are never reached. This analysis should help respond to misplaced concerns of water users that channel maintenance instream flow needs will deprive them of water.

Displaying Geomorphic Implications

A channel/floodplain inundation analysis is useful to evaluate how well the computed channel maintenance flows fit the channel and the floodplain and provides a preliminary assessment of the degree to which streamside vegetation may be inundated. Analysts can develop graphs from cross-section data, stage-discharge rating curves, and hydraulic modeling if necessary. The analysis serves to verify the extent to which the 25-year recurrence flow or other flow frequencies inundate the floodplain to provide for important riparian vegetation maintenance function. The cross-section in figure 11 illustrates how the channel maintenance flow regime fills the channel and inundates the floodplain.

Implementation Strategies

This section describes strategies for implementing studies following the previously described scientific channel maintenance concepts and principles. Analysts need to recognize that they may find situations where short time frames and limited flow and sediment data will require modifications or substitutions in the approach described.

Scales of Application

Two general categories of analysis are recognized:

- **Site-specific application** appropriate for projects; and
- **Broad-scale application** such as basin-wide collaborative watershed planning.

Quantitatively estimating channel maintenance instream flows is a complex endeavor best conducted at the site-specific level of application. Accordingly, these

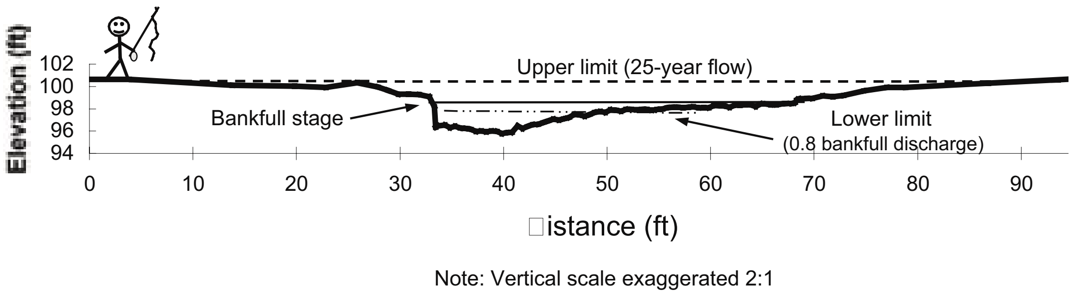

Figure 11—Channel and floodplain cross-section plot of the South Fork Cache La Poudre River, Colorado. Near to true scale plots can be used to evaluate the relationship between channel maintenance flow stages, flow frequencies, and the degree of inundation provided by the channel maintenance flow regime for riparian vegetation maintenance. The plot above has a 2:1 vertical exaggeration meaning that the channel appears deeper than it actually is. The stick figure fisherman is scaled to be 6 feet tall to provide true scale perspective.

guidelines focus on site-specific application. Broad-scale application at the watershed or basin level must often rely on less detailed field data. In these instances, the scientific concepts contained in this approach will need to be extrapolated to particular geographic areas and streams of interest.

If extrapolation is necessary, site-specific analysis at a limited number of representative sites is highly recommended to test if the extrapolated concepts apply to the geographic area of interest. The extent of local verification needs to be determined in each instance. For example, extensive bedload data sets useful for supporting the extrapolation of channel maintenance concepts exist for National Forest sites in Idaho, Oregon, and Colorado.

Setting the Context of the Analysis

Developing a study strategy is an important first step in applying this approach. The scope and detail of the strategy may vary depending on the application, but strategic thinking, analysis, and planning are key to success.

Detailed instream flow studies require significant investments of time and money and may require years to complete. While this might be necessary in special cases involving judicial proceedings, it is not necessary in all cases. Obtain commitment from management for the duration of required studies so that resources match expectations and focus data collection on answering the question at hand.

The value that organizations, individuals, government agencies, and society place on individual streams varies. Stream designations such as Wild and Scenic Rivers, Outstanding Resource Waters, Blue Ribbon Trout Streams, those containing threatened or endangered species, and other designations are of great concern to the public. In many cases, guidance contained in Forest Plans prioritizes stream reaches or watersheds according to resource value. While differing approaches are used by individual Forests, all prioritizing schemes address pertinent local resource issues, are the result of a large amount of public input, and have been formalized in the planning process. Use this information base and build upon it if necessary. Typically, streams with high resource value should receive the highest priority for instream flow protection.

The competition between instream and off-stream consumptive uses of water is more intense in some streams than in others. Conflicting demands may occur in streams identified for water resource development, watersheds with private inholdings, and streams desirable for hydropower development. Other streams, such as those that are remote from population centers, unsuitable for water development, located within Wilderness areas or completely within National Forest boundaries where the agency controls access and rights of way, have less potential for conflict.

Large dams, diversions, or withdrawals that significantly alter the natural flow regime are more likely to alter channel morphology and function than run-of-the-river hydropower projects or minor diversions. Give priority to sites where a lack of channel maintenance flows may produce a potential significant downstream risk to life, damage to property, or environmental values. Alluvial rivers and streams are at greater risk of channel change as a result of modified flows than steep reaches with bedrock channel characteristics. Rivers and streams where riparian vegetation depends on water from the stream (losing reaches and arid western streams) are often at greater risk than streams that gain water from adjacent sideslopes and where riparian vegetation is less dependent on instream water for survival.

Selecting Specific Quantification Sites

Hydrology, geology, climate, vegetation, and land use within the watershed influence water and sediment sources, and the interaction of these factors combine to determine the nature, distribution, and condition of stream channels.

Stream classification, such as the system proposed by Rosgen (1996) and Montgomery and Buffington (1997, 1998), can be a valuable tool for understanding and assessing stream adjustability. In mountain watersheds, alluvial valleys and alluvial reaches are commonly interspersed with bedrock-controlled segments and it is essential to view the entire drainage network as a whole system. At the simplest level, two major channel types, strongly linked to geology and valley form, are important to channel maintenance.

The first of these, **unconstrained channels**, flow through the alluvial deposits of wide valley floors allowing the channel to adjust to changing flows, sediment transport regimes, and major modifications of riparian vegetation. Floodplains are usually present. Unconstrained reaches are common on low to moderate gradient rivers and may be an important local component of valley floors in mountainous topography. Because unconstrained channels are highly adjustable, channel maintenance concepts are most appropriately applied to them.

A second major channel type, **constrained channels**, flow in narrow valley floors, tightly bounded by valley walls with limited opportunity for lateral movement or alteration of the channel due to boulder or bedrock channel materials. Constrained channels typically have slopes greater than 3 to 4 percent and step-pool, cascade, or bedrock morphology. Floodplains, if present, tend to be discontinuous and poorly developed. The position of the constrained reach is often controlled by major geologic controls including landslides, moraines, outwash terraces, and tributary fans. Because constrained channels are relatively non-adjustable, a lack of channel maintenance flows has less severe consequences and these channels may be assigned a lower priority.

In addition to inherent characteristics, an evaluation of changes to the stream resulting from watershed disturbance and land use is useful. Begin by determining:

- **Watershed Condition.** Evaluate the degree to which the watershed has been altered by management activities (logging, grazing, road construction, fire history, etc.) and try to estimate the effect this has had on streams. Reid and Dunne (1996) provide one approach for evaluating sediment budgets and management impacts. Evaluate streams for evidence of recent aggradation or degradation. If evident, attempt to identify the cause. Causes may be natural (e.g., catastrophic flood, geologic uplift, climate change) or human-induced (overgrazing, dam failure, etc.), or some combination. The objective is to verify whether or not the stream is in a state of quasi-equilibrium. Streams that are significantly out of equilibrium may require modified analysis procedures.
- **Water Management Infrastructure.** Determine the number of dams, reservoirs, and diversions within the watershed and schematically outline the effect they have on the flow regime. Evaluate the degree to which the structures alter peak flows, annual volumes, low flows, or combinations of flows, and evaluate their significance to resource values and channel maintenance. Be especially aware of long-term impacts, such as channels that may have adjusted to new flow regimes below dams or diversion, or channels that have expanded as a result of increased runoff due to management activities (e.g., transbasin diversions, road construction, ski area development, urban expansion) or changed land-use practices. The approach proposed here needs to be modified for application below major dams, especially those that retain all bedload sediment. Application of channel maintenance flows are unlikely to return severely impacted systems to pre-disturbance conditions. These systems will require more complex and comprehensive flow management schemes and different analysis techniques.
- **Stream Modification.** Evaluate past and present channel clearing, bank protection work, and channelization. Examine the effect these activities have had on channel form and the ability of the channel to adjust in the future. Effects may be positive or negative, permanent or transitory, depending on the nature of the activity. Recognize that simply imposing a natural flow regime into these systems will seldom “turn back the clock” and restore system to pre-disturbance conditions.

Vegetation plays an important role in channel dynamics. The effect of riparian vegetation on channel form is scale-dependent and typically more important on small streams than larger river systems. Evaluate the ability of streamside vegetation to be maintained and to reproduce under reduced flow regimes. Attempt to determine whether streamside vegetation depends on in-channel flows or groundwater connectivity for survival. Evaluate the general hydrologic relationship between surface and groundwater with an eye toward determining if the reach is a gaining (the local groundwater flow regime tends to feed the stream) or a losing reach (water generally moves from the stream to support the local groundwater table). Losing reaches are more likely to need instream flows to maintain streamside vegetation especially in arid or semiarid environments.

Based on an integrated evaluation of watershed characteristics, channel adjustability, and management impacts, select channel maintenance instream flow quantification sites having the following physical characteristics:

- Select perennial, alluvial, unconstrained, gravel-bed channel reaches.
- Avoid bedrock and bedrock-controlled reaches.
- Avoid reaches with gradients greater than 3 to 4 percent.
- Avoid braided reaches.
- Select reaches that are in relative quasi-equilibrium (i.e., avoid reaches that are actively aggrading/degrading).
- Select sites with evident natural alluvial features (floodplains, bars, vegetation).
- Avoid reaches directly impacted by roads, bridges, buildings, diversions, dams, channel structures, heavy livestock use, or any kind of human-induced alteration.
- Avoid reaches immediately below dams and reservoirs.
- Locate study transects within reaches on relatively straight segments between meander bends.
- Select reaches with reasonable access for repeated measurements.
- Give preference to sites with existing streamflow and bedload data.

General Data Needs

The channel maintenance quantification approach is facilitated by site-specific hydrologic, sediment, channel geometry, and vegetation data. Table 2 shows useful data and its application in the analysis.

Hydrologic and Sediment Data

Streamflow and bedload transport data at the quantification site greatly facilitates application of this approach. Where measured flow or sediment data are unavailable or unattainable in a reasonable time, models or other extrapolation techniques may be required. Although numerous techniques are available to estimate discharge and model bedload transport at ungaged sites, site-specific sediment and flow data minimize many of the technical objections that may be raised about a channel maintenance quantification.

Measured bedload data provide direct physical evidence of the sizes and amounts of bedload sediment transported through the reach under various flow conditions. Collecting quality data and adherence to standard data collection and analysis protocols are essential.

Bedload sediment transport is extremely variable. Even with careful site selection and rigorous field technique, inherent natural and sampling variability is high.

Table 2—Types of hydrologic, sediment, channel geometry, and streamside vegetation and the uses of that data in a channel maintenance instream flow analysis.

Data category	Type of data	Use of data
Hydrologic	Long-term daily mean discharges (flow duration)	Compute cumulative bedload sediment transport; magnitude-frequency analysis; compute long-term water allocation time series
	Peak flows (flow frequency)	Estimate upper limit of the channel maintenance hydrograph
Sediment	Bedload transport data	Compute cumulative bedload sediment transport; conduct magnitude-frequency analysis
	Bedload and bed-material particle size distribution	Estimate lower limit of the channel maintenance hydrograph
Channel geometry	Site map, photographs, channel cross-sections, longitudinal profile, bankfull stage (discharge), stage-discharge rating curve, bed-material size distribution	Characterize the quantification site, estimate bankfull discharge, provide a data base for monitoring channel change over time, evaluate how flows fit the physical dimensions of the channel, and support various aspects of the analysis
Streamside vegetation	Specific parameters determined by study team	Determine the relationship between discharge and streamside vegetation

Ideally, the data should span several years and represent a range of flow conditions from wet through dry years since rating curves may shift from year to year. Sampled rates of bedload transport must cover the full range of flows capable of transporting sediment in the stream. As a practical matter, technically supportable sediment rating curves require a minimum of 20 data points well dispersed over a range of flows and may be obtained in as little as one runoff season depending on flow conditions. In most cases, the ability to collect data at flow levels exceeding bankfull stage is a constraining factor.

Sampling Bedload Transport

The Helley-Smith bedload sampler (Helley and Smith 1971; Emmett 1980) is commonly used for bedload measurements in the United States. The U.S. Geological Survey recommends using the recently developed Federal Interagency Sedimentation Project US BLH-84 bedload sampler for new projects. For consistency, use the same sampler throughout the course of the study at the same site. Regardless of device, sampling is generally carried out at uniform cross-sections similar to sections for discharge measurement or suspended sediment sampling. The recommended procedure is to conduct two traverses of the stream, sampling at least 20 equally spaced cross-channel locations on each traverse with a sampling duration of 30 or 60 seconds at each vertical (Emmett 1981). Ryan and Troendle (1997) provide specific guidance for measuring bedload in coarse-grained mountain channels.

Details of field and computation techniques for bedload and suspended sediment measurements are available in the U.S. Forest Service publication *Methods for Collecting and Analyzing Fluvial Sediment Data* (USDA Forest Service 1988) and the U.S. Geological Survey publication *Field Methods for Measurement of Fluvial Sediment* (Edwards et al. 1999).

It may be advantageous to use bedload traps in lieu of Helley-Smith samplers in wadeable channels with coarse bed material (Bunte et al. 2001; Bunte et al. Submitted). Bedload traps are particularly useful where the initiation of gravel transport is all that is required or initiation of gravel motion information is needed at a large number of sites.

Streamflow Data

The preferred choice for any hydrologic analysis is to have a long-term discharge record at the quantification site. Records exceeding 20 years are more representative of the long-term and reduce the influence of drought or wet years on the record. In many cases records of less than 20 years will need to be extended and correlated using hydrologically similar long-term stations.

In the absence of a stream gaging station near the quantification site, initiating a program to collect continuous flow data for a short period of time at the site is often advantageous. Short-term concurrent flow measurements at the quantification site can be used to extend its record to that from an existing long-term gage (Moog et al. 1999). Discharge at ungaged sites can also be estimated using the index station method (Searcy 1959), station correlation techniques (Searcy 1960; Hirsch 1982; Gordon et al. 1992), or regional dimensionless flow duration curves (Emmett 1975).

Federal agencies have adopted the Log-Pearson Type III distribution to analyze peak flow frequency data at locations where a systematic record of peak flows is available. The United States Water Resource Council (1982) Bulletin No. 17B, *Guidelines for Determining Flood Frequency*, presents the currently accepted methods for analyzing peak flow frequency data at gaging stations. A variety of regional techniques and procedures have been published by the U.S. Geological Survey and others for estimating peak discharges at ungaged sites either by river basin (for example, Thomas and others 1963 Snake River Basin), specific states (for example, Thomas and Lindskov 1983 state of Utah), or geographic regions (for example Hedman and Osterkamp 1982, western United States).

Channel Geometry Data

Procedures for conducting a channel geometry survey to characterize the nature of a study stream reach are discussed in *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson et al. 1994). Examples of channel geometry data analysis techniques are illustrated in *The Channels and Waters of the Upper Salmon River Area, Idaho* (Emmett 1975) and reported in standard texts such as Dunne and Leopold (1978).

An important part of any channel geometry survey includes a detailed site map of the study reach showing a plan view of the reach with sufficient accuracy to clearly depict channel features, floodplains, terraces, data collection sites, and other features. The site map should use surveying and mapping techniques such as plane table mapping, total station surveys, or aerial photographs. A good set of aerial or ground photographs can be a valuable supplement to the site map.

Normally, cross-sections are located in straight reaches between meanders in sufficient number to characterize the variability of the study reach. Tie all cross-sections to permanent benchmarks and extend them across the channel well above bankfull stage to at least the predicted 25-year flow level or about 1.5 times bankfull depth.

The survey needs to include a longitudinal profile of the stream that establishes the elevation of the existing water surface, channel bottom, and the floodplain (bankfull stage). Normally, longitudinal profiles extend a length of approximately 20 times bankfull channel width along the channel. Data from the longitudinal profile survey is used to identify bankfull stage at cross-sections.

The best indicator of bankfull stage is the level of the active floodplain as identified by the presence of depositional surfaces (USDA Forest Service 1995, 2002, 2003). A reach averaging approach, based on the identification of bankfull stage at multiple locations along a longitudinal profile, provides a better estimate of bankfull stage than selecting bankfull stage at a single cross-section (Dunne and Leopold 1978).

Discharge Rating Curves

The best way to determine flow quantities for various levels of water in a stream is to make a number of discharge measurements with a current meter and develop a stage-discharge relation, commonly called a rating curve. Once the curve is constructed, discharges can be accurately estimated from the water level, or stage, in a stream (assuming the bed remains stable). A rating curve is essential for estimating discharge associated with bankfull stage and to quickly determine discharge when bedload measurements are made. Discharge measurement procedures and the development of stage-discharge relations and their adjustment are described in detail in U.S. Geological Survey, Techniques of Water-Resources Investigations (Buchanan and Somers 1969; Kennedy 1984) and summarized in the U.S. Geological Survey's *National Handbook of Recommended Methods for Water-data Acquisition* (U.S. Geological Survey 1977). A tutorial on measuring stream discharge is available on CD-ROM from the USGS (Nolan and Shields 2000).

Particle Size Data

Wolman pebble counts (Wolman 1954) are useful to characterize the surface particle size distribution of the bed material making up the study stream. The particle size distributions of the subsurface material, bars, and bank materials are often also useful to understand sediment transport processes. Procedures for bed-material sampling of coarse material in gravel-bed rivers are discussed in the U.S. Geological Survey publication *Field Methods for Measurement of Fluvial Sediment* (Edwards et al. 1999) and other publications, for example Yuzyk (1986) and Bunte and Abt (2001).

Streamside Vegetation Data

Vegetation data is collected to determine if streamside vegetation depends on soil water (or water-influenced environmental conditions) derived from channel flows. Due to high variability in stream-groundwater interactions among drainages and along stream channels and the diverse response of streamside vegetation, data-intensive site-specific analysis is required. The linkage between the stream and alluvial aquifer is best determined by observation and inference based upon groundwater wells, or piezometers, and river stage data, or if indicated, soil water chemistry, including isotopes.

Post-Project Management and Evaluation

Administration of channel maintenance instream flows becomes important once an instream flow allocation is acquired. A key element of post-project evaluation is verifying that the instream flows obtained are actually flowing down the channel in the manner specified. Stream gages established during the study can be especially valuable to assist with post-project evaluations.

Follow-up measurements are essential for determining if the established channel maintenance instream flow regime is actually present and adequate to maintain the capacity of the channel and maintain streamside vegetation. If the channel is adjusting to the imposed flow regime in an unacceptable manner, either causing increases or decreases to channel dimensions or streamside vegetation, corrective measures may be needed. This is best done in the context of adaptive management.

Channel maintenance post-project evaluations should as a minimum address the following key questions:

- Is the channel receiving the range of flows determined necessary in Forest Plans, special-use permits, or by State permit or decree?
- Are the dimensions of the channel stable compared to undiverted reference reaches?
- Is sediment, both in size and volume, being distributed and transported in such a way as to prevent either long-term aggradation or degradation?
- Is there any change in channel capacity over time due to vegetative ingrowth or sediment deposition?
- Is streamside vegetation in a maintaining or a declining trend?

The following list identifies critical data elements useful to support post-project management and evaluations:

- Discharge information (preferably from a continuously recording stream gage).
- A permanent record of stream cross-section dimensions and elevations, referenced to a permanent benchmark.
- Channel geometry data at permanent sites to observe any shifts in channel width, depth, or slope.
- Bedload sediment measurements, including particle size distribution and stream discharge over a wide range of flows.
- Channel material size distribution in the reach.
- Longitudinal profile to document changes to slope and pool spacing.
- Monumented photo-points to document channel and vegetation changes over time.
- Riparian vegetation transects to document species composition and distribution changes.
- A record of flow diversions and natural flows.

Procedures for establishing permanent reference sites to measure change to the physical character of stream channels and to monitor trends in fluvial and geomorphic conditions are discussed in *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson et al. 1994).

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