The Evolution of Channel Maintenance Science in the Forest Service

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Channel maintenance instream flows consist of a specified range and duration of flows designed to provide for the self-maintenance of alluvial stream channels. Channel maintenance flows provide for processes that determine the form of the physical channel. Agency scientists placed emphasis on physical channel form to satisfy constraints imposed by litigation in Forest Service reserved water rights claims. The original channel maintenance flow methodology was developed by Forest Service hydrologists in 1982 and the technical basis for channel maintenance flows and quantification approaches has evolved significantly over the last 20 years. Under the original approach, the channel maintenance hydrograph consisted of a rigid stepped hydrograph fixed in time and capped at bankfull discharge. Under current approaches, the flows necessary to maintain channels are seen as a naturally variable range of flows typically beginning at intermediate flows below bankfull discharge and including high flows that inundate the floodplain. While the original approach focused primarily on the need to transport sediment through the stream system, more recent approaches recognize that the required flows must also provide sufficient low and high flows to sustain streamside vegetation. As understanding of gravel-bed streams processes and the linkages between streamside vegetation and streamflows increases, additional improvements and refinements to quantification approaches are likely.

Keywords: *channel maintenance, instream flows, favorable conditions of water flows*

Introduction

The Forest Service attempted to acquire channel maintenance instream flows in many adjudications throughout the western United States during the 1980s and 1990s. These instream flows claims have generally failed, their failure attributed to hostile state court forums, the stringent test established by the U.S. Supreme Court for implied reserved water rights, and the difficulty of quantifying instream flow water rights for dynamic hydrologic stream systems (Witte 2001). This paper concentrates on the scientific aspects of channel maintenance flows and the extraordinary change in scientific thinking pertaining to channel maintenance that has occurred within the Forest Service and the scientific community between the origination of the first channel maintenance methodology in the 1980s and the present. A brief discussion of the legal framework surrounding the development of channel maintenance instream flow concepts and pertinent court decisions is provided to establish context.

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The Legal Context of Channel Maintenance Instream Flows

The genesis of the doctrine of federal implied reserved water rights occurred in 1899, but it was not until 1963 that the doctrine was expanded by the United States Supreme Court in Arizona v. California to include national forests, parks, and recreation areas. Prior to the court's decision in 1963, the application of the doctrine (which holds that when Congress reserves land it impliedly reserves water in a quantity sufficient to meet the purposes for the reserve) was widely believed to be restricted to Indian reservations.

Following the expansion of the doctrine to other federal reserves, the Forest Service began filing for instream flows on National Forest System lands. These efforts occurred in state water courts throughout the West pursuant to the limited waiver of federal sovereign immunity provided by the McCarren Amendment (passed by Congress in 1952). This amendment gave state water courts jurisdiction to hear federal water right claims.

Litigation of one of the first claims filed under the federal implied reserved water rights doctrine for National Forest System lands occurred during the adjudication for the water rights of the Rio Mimbres on the Gila National Forest in New Mexico. Instream flow claims for the benefit of fish, recreation, and aesthetics were filed under the

authority of the Creative Act of 1891 and the Organic Administration Act of 1897.

These claims were denied in 1978 by the United States Supreme Court in United States v. New Mexico by a narrowly split (5 to 4) decision. The majority ruled that the Forest Service could not claim federal reserved water rights for Multiple-Use Sustained-Yield Act purposes and strictly construed the purpose for which water could be claimed under the doctrine on National Forest System lands to two purposes, "securing favorable conditions of water flows and to furnish a continuous supply of timber."

In an effort to protect stream flows for these narrow purposes on National Forest System lands, the Forest Service defined favorable conditions of water flows to include healthy stream channels. Under the constraints imposed by the Supreme Court, the Forest Service devised a methodology to determine the amounts of water necessary to maintain stream channels in a condition suitable for "securing favorable conditions of water flows." The flows quantified under this approach came to be known as channel maintenance instream flows. Due to the constraints of the federal impliedly reserved water rights doctrine, only the minimum amount necessary to secure favorable conditions of water flows could be claimed (Witte 2001).

Channel maintenance flows are non-consumptive instream flows specifically designed to maintain the physical characteristics of the stream channel (Schmidt and Potyondy 2004). Providing for channel maintenance requires that stream channels support healthy streamside vegetation and have flows of sufficient magnitude, duration, frequency, and timing to maintain channel morphology so that the capacity of the channel to convey natural flows is unimpaired over the long term.

The Original Channel Maintenance Methodology

The original channel maintenance methodology was primarily developed by Forest Service hydrologists David Rosgen and Hilton Silvey (Rosgen 1982) and are based to a large extent on concepts contained in the classic geomorphology textbook, "*Fluvial Processes in Geomorphology*" by Leopold, Wolman, and Miller (1964). Subsequent personal involvement in Colorado's Water Division One litigation by Luna Leopold, Emeritus Professor of Geology at the University of California, Berkeley, former Chief Hydrologist of the U.S. Geological Survey, and one of the world's leading authorities on river hydraulics and geomorphology, gave credibility to these ideas.

The Forest Service's original channel maintenance procedure was documented in the Forest Service directives system, Forest Service Handbook 2509.17, Chapter 30, "Procedure for Quantifying Channel Maintenance Flows" (USDA Forest Service 1985). In it, channel maintenance flows are defined as, "A range and duration of in-channel flows necessary to maintain the stability and effective function of the stream channel. This includes those flows which are necessary to provide for the self-maintenance of the stream channel network so as to retain its capacity for passing flood discharges and minimize channel erosion and/or sediment deposition associated with instability or disequilibrium conditions. The consequences of not maintaining channel stability include channel aggradation, channel erosion, floodplain encroachment, vegetation encroachment, changes in hydraulic geometry, and reduced channel capacity with resultant increased risk of flooding and associated resource damage."

The channel maintenance procedure was intended for application to snowmelt dominated, perennial, alluvial channels capable of adjusting their dimension, shape, pattern, or gradient, or several of these characteristics, in response to changes in streamflow (Rosgen et al. 1986). Generally accepted concepts used by engineers, hydrologists, and geomorphologists formed the basis for the channel maintenance procedure.

Three basic flow components were considered essential for a channel maintenance flow regime: (1) a peak flow (bankfull discharge); (2) a low flow (baseflow discharge); and (3) snowmelt rise and recession discharges (Figure 1). Bankfull discharges were considered essential because flows near bankfull have been shown to move the most sediment over the long term (Wolman and Miller 1960) and are frequently referred to as channel-forming flows. Baseflows were considered necessary to maintain the "thread of the stream" (the thalweg channel) by migrating sediment from riffles to pools and preventing vegetation encroachment and seedling establishment in the active channel by maintaining high water tables. Gradual rise and recession flows were included to avoid rapid changes in stage which might cause accelerated bank erosion and to allow for a duration of flows that mimics the natural hydrograph. This was accomplished by beginning the claim when average annual flow was first attained during the spring snowmelt hydrograph. Flows were then gradually increased in 10 percent increments between the average annual and bankfull discharges resulting in a stair-stepped hydrograph up to and including bankfull discharge. The recession limb of the hydrograph was constructed in a similar manner except that the duration of recession flows was constrained to one day under the concept of the existence of a hysteresis effect, allowing for a rapid recession. Hysteresis assumes

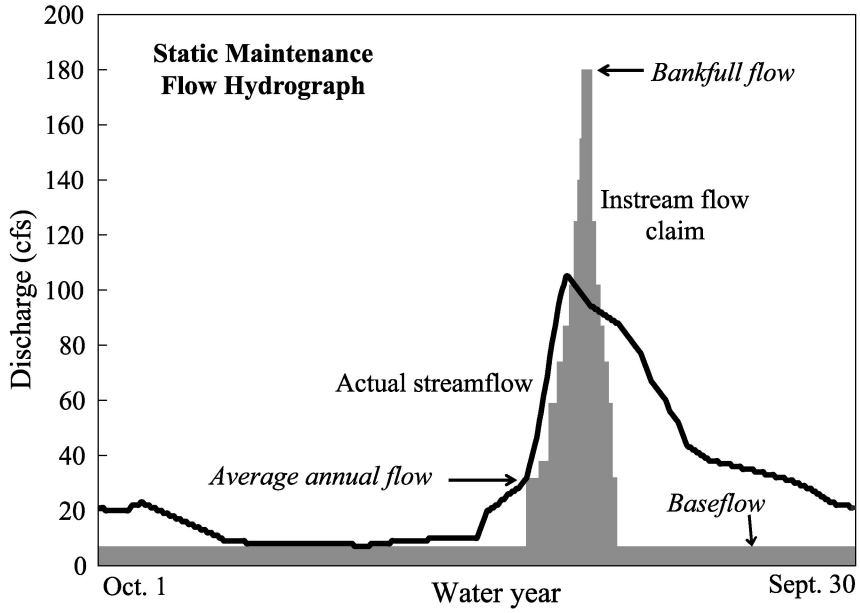

Figure 1. The original form and elements of the static maintenance flow hydrograph consisting of gradual rising steps, a cap at bankfull discharge, a recession limb, and year-round baseflows.

that the majority of the sediment is transported during the rising limb and therefore flows during the recession portion of the hydrograph are not as critical for sediment movement and channel maintenance. Therefore, flows after the peak were allowed to decrease rapidly relative to the rise.

A typical static channel maintenance flow hydrograph is constructed using this procedure (Figure 1). The term static is used because the shape of the hydrograph was fixed in quantity and time once it was initiated by the occurrence of average annual flow. A static form was required because the procedure was developed under the assumption that the instream flow claim must meet the basic requirements of State water rights law, that is, in order to provide for certainty in water administration the amounts claimed needed to be precisely stated with respect to time and amount. Details of the procedure for constructing maintenance flow hydrographs can be found in Forest Service Handbook 2509.17, Chapter 30 (USDA Forest Service 1985).

Significant technical points of contention included questions of whether average annual flow was the appropriate required discharge for the beginning of channel-maintaining sediment transport, whether peak flows constrained to no more than bankfull discharge were adequate to maintain stream channels, and whether baseflows played any important role in maintaining physical channel characteristics.

Development of the Dynamic Hydrograph

Technical problems with the static nature of the channel maintenance flow hydrograph first surfaced during the 1991 trial of an adjudication encompassing the South Platte River and its tributaries, hereafter referred to as Water Division 1. During the trial, experts for the State of Colorado analyzed the entire period of daily flow records for 19 USGS gaging stations and superimposed the static hydrograph to determine how often the claim would actually be met. The analysis showed that actual hydrographs varied from year to year to such an extent that the static claimed hydrograph frequently misaligned with the occurrence of peak flows (e.g., Figure 2). Note that in this example bankfull discharge occurs in the stream, but at the time of its occurrence, significantly lower amounts of water are claimed due to the fixed, static nature of the claim process. Likewise, when bankfull discharge is claimed, natural stream flow for that year has already receded so that water equal to bankfull is unavailable. The net result is that in this high flow year scenario, the bankfull discharge required to maintain the channel would fail to be claimed by the Forest Service.

The pattern from the 19 streams examined showed that the channel maintenance flows claimed would only reached bankfull discharge 15 to 19 percent of the years of record (Gordon 1995). This low occurrence of bankfull discharge was significantly less than the 67 percent of the years (every two out of three years) that Forest Service technical testimony had argued was necessary for the channel to be maintained. The State concluded its testimony by pointing out that even if the claim was granted, the Forest Service would fail to achieve the desired maintenance objective. Conceding, but never refuting the analysis, the Forest Service proceeded to develop the dynamic hydrograph in a span of several weeks to overcome the deficiencies of the static approach.

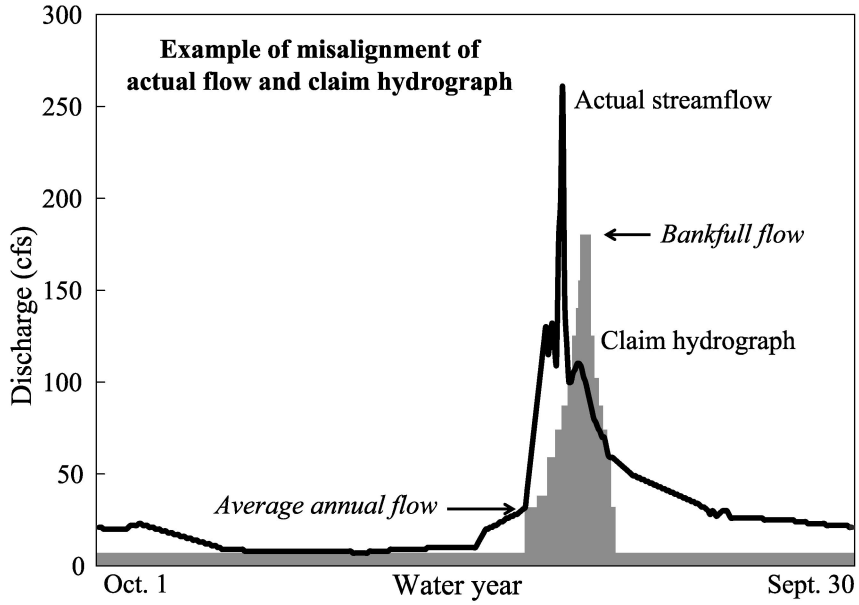

Figure 2. A typical example of misalignment between actual streamflow and the static maintenance flow hydrograph.

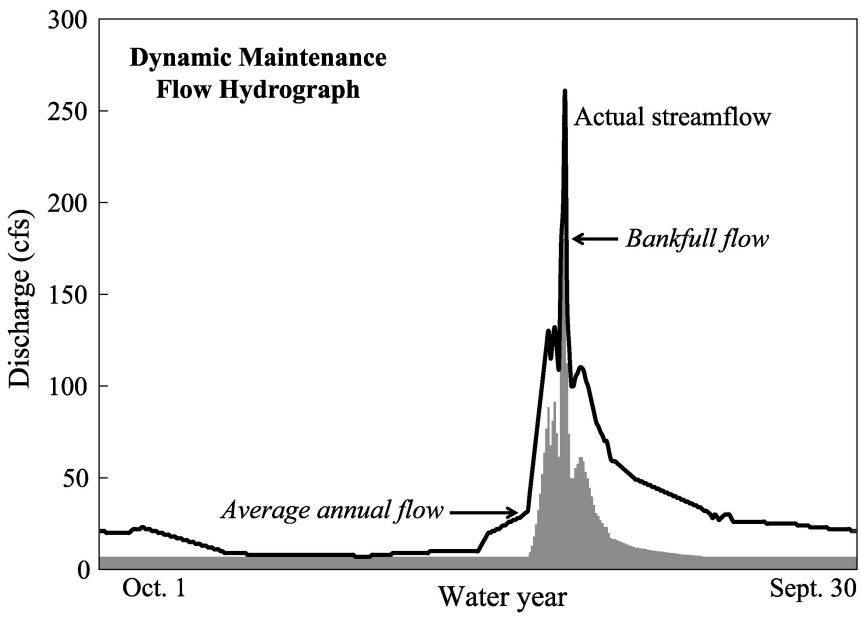

Figure 3. The form and elements of the dynamic maintenance flow hydrograph structured so that the claim is only made when water is in the channel and claimed flows are proportionally distributed so that more water is claimed at flows approaching bankfull discharge.

The "dynamic" hydrograph was so named because it rises and falls with natural stream flows. To achieve this, the dynamic claim hydrograph was structured and positioned so that it only claimed flows when water was actually in the stream channel (Figure 3). The dynamic form retains most of the essential features of the static form: claim initiation beginning with attainment of average annual flow, a maximum peak set at bankfull discharge, and a baseflow component. However, instead of the "stairstep" appearance of the static claim, the dynamic form claimed a sliding percentage of the streamflow such that more water was claimed at flows closer to bankfull. Amounts were calculated according to the following formula:

$$\text{Claimed flow} = Ql + \left((Qs - Ql) \times \left(\frac{Qs - Qa}{Qb - Qa} \right) \right)$$

where: Qs = actual streamflow, Ql = baseflow, Qa = average annual flow, and Qb = bankfull flow.

Positioning the claim under actual stream flows eliminated a primary deficiency of the static hydrograph by assuring that the claim was active only when flows up to the channel forming bankfull discharge occurred. Scientifically this provided an improved solution of the channel maintenance flow problem. Administratively however, the dynamic solution was complex and problematic because it might not meet fundamental requirements of a water right with respect to time and amount and it would be difficult to administer in practice. In addition, other technical points of contention pertaining to bankfull discharge, the initiation of sediment movement at average annual flow, and the need for baseflow remained.

In the final decision in the Water Division 1 litigation in 1993, Judge Behrman denied both the static hydrograph and dynamic hydrograph based channel maintenance claims. The judge observed that the technical challenges to quantify channel maintenance claims had not been adequately met and noted that it might be impossible to do so (Gillilan and Brown 1997). He further commented that the hurried time constraint imposed on the development of the dynamic hydrograph in particular was not the ideal environment for careful scientific study and suggested that a proposal developed under calmer and more scholarly circumstances would be appropriate (Gordon 1995).

CURRENT APPROACHES

The USDA Forest Service Stream Systems Technology Center was established in 1992, in part, to improve the scientific understanding of channel maintenance flows. Since that time, they have consulted with a wide array of scientists in the Forest Service, other agencies, universities, and consultants, with the aim of arriving at a consensus on the best science available to address this issue.

While there is still diversity of opinion on many technical aspects of channel maintenance, initial consultation with the scientific community identified four technical areas that were at odds with then existing Forest Service approaches:

1. Channel maintenance requires a range of flows, including peak flows exceeding bankfull discharge;
2. In alluvial gravel-bed streams, required channel maintenance flows need to periodically move the caliber of sediment making up the bed of the channel (Phase 2 transport);
3. Baseflows, while perhaps necessary for other important ecological functions, play an insignificant role in maintaining the physical form of the channel; and
4. Streamside vegetation plays an important role in maintaining stream channels.

Sediment Transport

A major change in scientific thinking beginning in the late 1980s and through the 1990s is the concept that channel maintenance in gravel-bed streams centers around a range of intermediate flows rather than bankfull discharge alone. While Emmett (1976) was the first to propose two distinct phases of transport in armored channels as early as 1976, it was not until the 1980s that others expanded the concept to describe phases of bedload transport in gravel-bed streams (Jackson 1981; Jackson and Beschta 1982; Beschta 1987; Ashworth and Ferguson 1989; Warburton 1992). During the 1990s, numerous other scientists confirmed that intermediate discharges transport mainly sand (Phase 1 transport) whereas discharges near or above bankfull transport coarser bedload (Phase 2 transport) (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). While there is widespread agreement that movement of coarse gravels beginning at discharges associated with Phase 2 transport and continuing on to higher discharges is important for channel maintenance, considerable uncertainty exists regarding the best manner to identify this initiation discharge and numerous approaches have been proposed (Emmett 1999; McNamara et al. 2000, Ryan et al. 2002, Whiting and King 2003, Schmidt

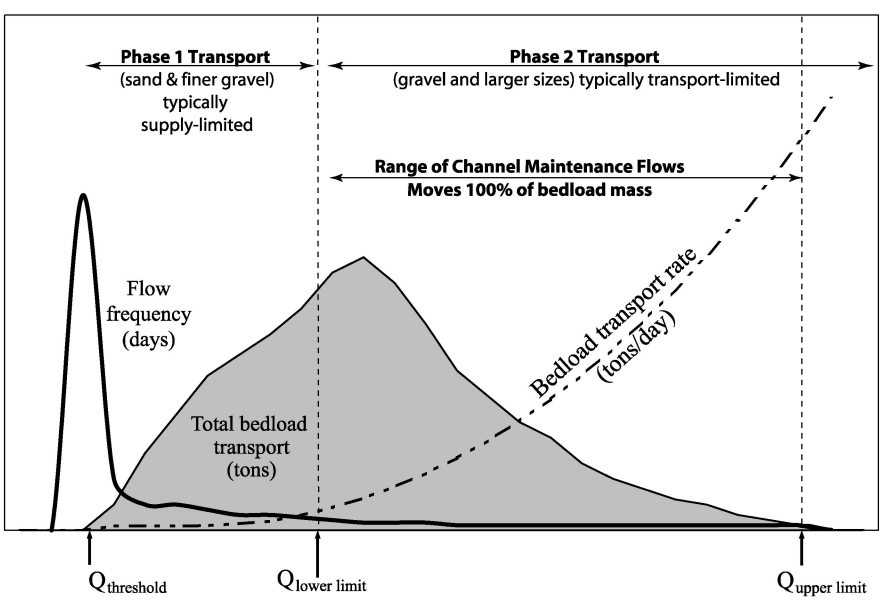

Figure 4. A conceptual model of total bedload transport that forms the basis for the current proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States.

and Potyondy 2004). Regardless of methodology used to identify initiation, investigators generally have found that Phase 2 transport begins at discharges ranging between 60 to 100 percent of bankfull discharge (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker 1997; Ryan et al. 2002, 2005; Trush et al. 2000).

Schmidt and Potyondy (2004) summarize the current science and develop a conceptual gravel-bed river total bedload transport model (Figure 4) which forms the basis for a proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States. The approach is appropriate for quantifying channel maintenance flows on perennial, unregulated, snowmelt-dominated, gravel-bed streams with alluvial reaches. Under this approach essential channel maintenance flows begin at a lower limit of discharge associated with the onset of Phase 2 bedload transport (80% of bankfull is used as an example in the diagram) and includes all flows up to an upper limit set at the 25-year flood stage (Figure 5). All flows from the lower limit to the upper limit are claimed as necessary for channel maintenance whenever these flows occur assuring that claims are made only when water actually exists in the stream channel. While all high flows contribute to sediment transport and channel morphology, flows exceeding the 25-year event are excluded as unnecessary for channel maintenance because they are thought to play a role primarily in valley maintenance (Hill et al. 1991). In addition, because extreme high flood flows may cause property damage, they are excluded for practical purposes because it is difficult to characterize these high flows as a "favorable condition of water flow." The current hydrograph structure claims considerably less water than either the static or dynamic approaches because it places greater reliance on short duration flows approaching and exceeding bankfull to accomplish the necessary sediment transport.

A remarkable shift in our understanding of the range of sediment transporting flows needed for channel maintenance has occurred (see Figure 6). The original peak flow structure began with a conservative estimate of when bedload may begin to move in some channels, typically a value of around 20% of bankfull discharge, and was limited to flows no higher than the bankfull discharge contained within the main channel, excluding flows that would spill onto the floodplain. The current peak flow approach begins with the initiation of coarse sediment transport making up the bed of the channel, commonly a value ranging from 60 to 100% of bankfull discharge and having an average of about 80% of bankfull discharge. The flows exceed bankfull to a significant degree and include flows that spill onto the floodplain, recognizing that the floodplain is an extension of the channel that needs to be periodically disturbed in order to maintain floodplain processes and streamside vegetation.

Streamside Vegetation

A parallel shift in thinking has also occurred regarding the role of vegetation in channel maintenance flow processes. Under the original approach, vegetation was essentially considered an "enemy" of channel maintenance and the original approach argued that baseflows were necessary to prevent vegetation encroachment within the channel while failing to acknowledge the role streamside

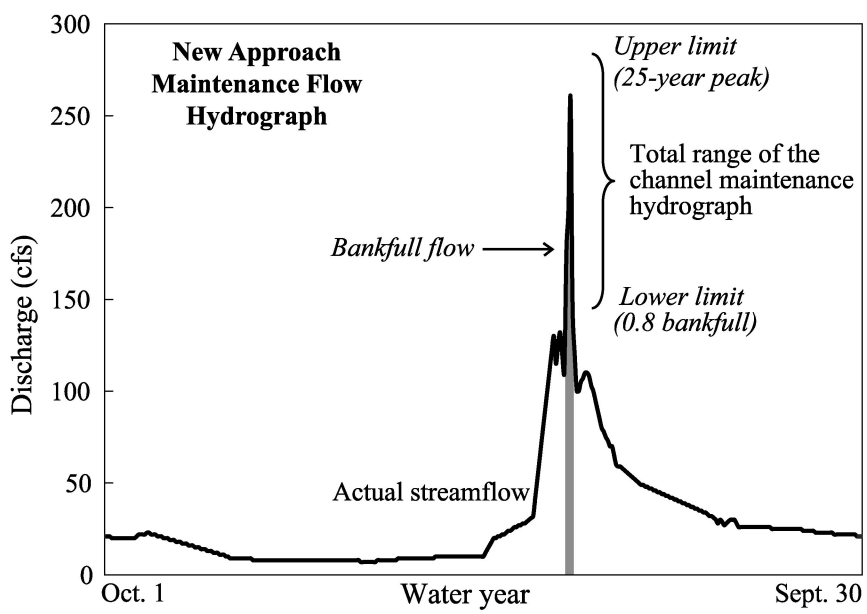

Figure 5. The form and elements of the maintenance flow hydrograph under the current approach. Channel maintaining flows begin at a lower limit with the initiation of coarse gravel (Phase 2 transport) and include flows up to an upper limit, the 25-year peak flow.

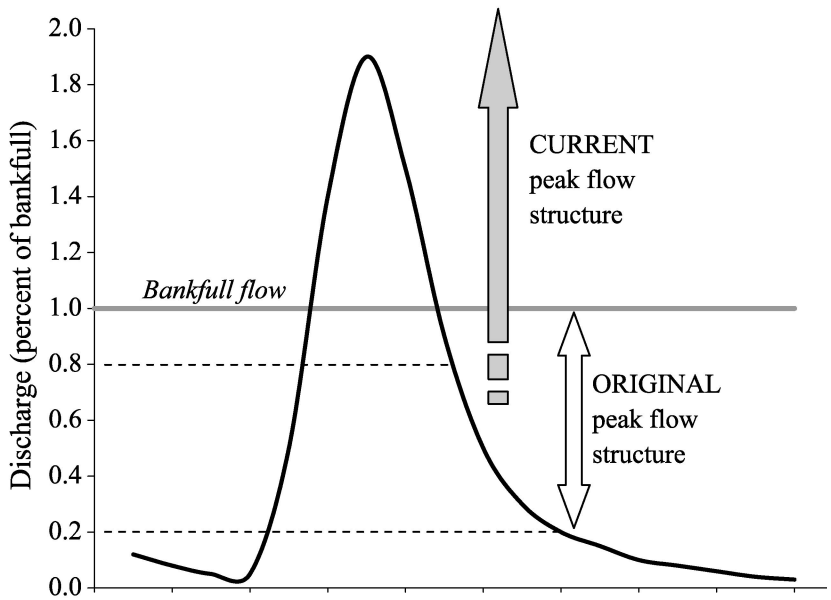

Figure 6. An illustration of the remarkable shift in the range of flows considered necessary for channel maintenance between the original static hydrograph approach of the 1980s and the range of flows considered to necessary today.

vegetation plays in providing for streambank stability. The primary concern centered on possible detrimental effects to the channel that might result from in-channel vegetation blocking orderly sediment transport through the system.

The current approach treats streamside vegetation as an essential part of a well-maintained channel by recognizing that 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 (Schmidt and Potyondy 2004). Toward that end, high flows exceeding bankfull stage are needed to provide for periodic disturbance to assure regeneration and to scour vegetation from the channel. These high flows can substantially influence channel dynamics, encourage floodplain scour and sediment deposition, provide for water storage and nutrient cycling and the periodic disturbance required by streamside and floodplain plant communities (Jackson et al. 1987; Gebhardt et al. 1989; Gregory et al. 1991; Stromberg et al. 1991; Jackson and Beschta 1992; Mahoney and Rood 1993).

The association between riparian vegetation and streamflow is particularly evident in arid environments and year-round baseflow may also be needed to sustain protective streambank vegetation in losing reaches in arid and semi-arid regions (Stromberg and Patten 1996). However, in many 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 and mountainous sideslopes contribute water to maintain soil moisture and baseflow making instream baseflows unnecessary (Schmidt and Potyondy 2004).

Conclusion

The goal of this paper is to describe the differing approaches to channel maintenance that the Forest Service has employed over the years. Science by its very nature is dynamic and continually expanding in its understanding. Furthermore, disciplines, especially relatively young sciences such as fluvial geomorphology, operate under accepted paradigms until new paradigms are adopted and this is part of the process that has been especially evident over the last decade (Kuhn 1962). The change implemented by the Forest Service in its channel maintenance technology in response to challenges to its science in legal proceedings and other forums is a positive, rather than a negative attribute.

More hydrologists and geomorphologists work in the field of fluvial geomorphology today than at any time in the past. Numerous papers are being published, research is in progress, and understanding of geomorphic processes is expanding and changing as interest in the disciple continues. By discussing and understanding the strengths, weaknesses, and appropriateness of past methodologies, it may be possible to encourage the development of improved ideas and approaches.

Two specific areas need further research with respect to current channel maintenance science: First, much remains to be learned about sediment transport science in coarse-grained gravel bed channels typically found in the mountainous watersheds of the national forests; Second,

much remains to be learned about streamside vegetation and species specific linkages between streamside vegetation and streamflows in mountain streams. As work in these areas continues, we can be certain that the science of channel maintenance will once again evolve in response to this new knowledge and the approach employed today may again need to be refined to reflect the new science.

Literature Cited

Ashworth, PJ; and RI Ferguson. 1989. Size-selective entrainment of bed load in gravel bed streams. *Water Resources Research* 25(4):627-634.

Beschta, RL. 1987. Conceptual models of sediment transport in streams. In: C.R. Thorne, J.C. Bathurst, and R.D. Hey (eds), Sediment Transport in Gravel-bed Rivers, John Wiley & Sons, Chichester, p. 387-408.

Carling, P. 1995. Implications of sediment transport in instream flow modeling of aquatic habitat. In: Harper, D.M. and A.J.D. Ferguson (eds), The Ecological Basis for River Management. John Wiley & Sons, Chicester, England, p. 17-32.

Church, M; JF Wolcott, and WK Fletcher. 1991. A test of equal mobility in fluvial sediment transport: behavior of the sand fraction. *Water Resources Research* 27:2941-2951.

Church, M, and MA Hassan. 2002. Mobility of bed material in Harris Creek. *Water Resources Research* 38(11):19-1 to 19-12.

Emmett, WW. 1976. Bedload transport in two large, gravel-bed rivers, Idaho and Washington. In: Proceedings of the 3rd Inter-agency Sedimentation Conference, Denver, Colorado, March 22-25, p. 4-101 to 4-114.

Emmett, WW. 1999. Quantification of channel-maintenance flows for gravel-bed rivers. In: D.S. Olsen and J.P. Potyondy (eds), Wildland Hydrology, American Water Resources Association, Herndon, Virginia, TPS-99-3, p. 77-83.

Gebhardt, KA, C Bohn, S Jensen, WS Platts. 1989. Use of hydrology in riparian classification. In: RE Gresswell, BA Barton, and JL Kershner (eds), Practical Approaches to Riparian Resource Management, USDI Bureau of Land Management, Billings, Montana, p. 53-59.

Gillilan, DM, and TC Brown. 1997. Instream Flow Protection: Seeking a Balance in Western Water Use. Washington, D.C., Island Press, 417 p.

Gordon, N. 1995. Summary of technical testimony in the Colorado Water Division 1 trial: Overview; January-December 1990; Greeley, Colorado. USDA Forest Service, Rocky Mountain Forest and Range Research Station, Gen. Tech. Rep. RM-GTR-270, 140 p.

Gregory, SV, FJ Swanson, WA McKee, and KW Cummins. 1991. An ecosystem perspective of riparian zones. *BioScience* 41(8):540-551.

Hill, M. T.; Platts, W. S.; Beschta, R. L. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. *Rivers* 2(3): 198-210.

Jackson, WL. 1981. Bed material routing and streambed composition in alluvial channels. Ph.D. Thesis, Department of Forest Engineering (Hydrology), Oregon State University, Corvallis, OR. 160 p.

Jackson, WL, and RL Beschta. 1982. A model of two-phase bed load transport in an Oregon Coast Range stream. *Earth Surface Processes and Landforms* 7:517-527.

Jackson, WL, and RL Beschta. 1992. Instream flows for rivers: maintaining stream form and function as a basis for protecting dependent uses. In: ME Jones and A Laeanen (eds), Interdisciplinary Approaches in Hydrology and Hydrogeology, American Institute of Hydrology: p. 524-535.

Jackson, WL, T Martinez, P Culpin, et al. 1987. Assessment of water conditions and management opportunities in support of riparian value: BLM San Pedro River Properties, Arizona. USDI Bureau of Land Management Service Center, BLM/YA/PT-88/004-7200, Denver, CO, 180 p.

Komar, PD, and SM Shih. 1992. Equal mobility versus changing bedload grain sizes in gravel-bed streams. In: P. Billi, RD Hey, CR Thorne, and P Tacconi (eds), Dynamics of Gravel-bed Rivers, John Wiley & Sons, Chichester, 73-93.

Kuhn, T. 1962. The structure of scientific revolutions. University of Chicago Press, Chicago, IL. 3rd ed. 226 p.

Kuhnle, RA. 1993. Fluvial transport of sand and gravel mixtures with bimodal size distribution. *Sedimentary Geology* 85: 17-24.

Lisle, TE. 1995. Particle size variations between bed load and bed material in natural gravel bed channels. *Water Resources Research* 31:1107-11018.

Leopold, LB, MG Wolman, and JP Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman, San Francisco, CA, 522 p.

Mahoney, JM, and SB Rood. 1993. A model for assessing the effects of altered river flows on the recruitment of riparian cottonwoods. Gen. Tech. Rep. RM-226, Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station: 228-232.

McNamara, ML, PC Klingeman, PD Bakke, and RJ Sullivan. 2000. Channel maintenance flows in the Upper Klamath Basin, Oregon. In: PJ Wigington, and RL Beschta (eds), Riparian Ecology and Management in Multi-Land Use Watersheds, American Water Resources Association, Middleburg, Virginia, TPS-00-2, pp. 53-58.

Petts, GE, and I Maddock. 1996. Flow allocation for in-river needs. In: River Restoration, G Petts and P Calow (editors). Blackwell Science Ltd, Oxford, England, p. 60-79.

Pitlick, J. 1994. Coarse sediment transport and the maintenance of fish habitat in the Upper Colorado River. In: GV Cotroneo and RR Rumer (eds), Proc. of the 1994 Conference Hydraulic Engineering '94, Vol. 2, ASCE Hydraulic Division, Buffalo, NY, August 1-5, p. 855-859.

Rosgen, D. 1982. A procedure and rationale for securing favorable conditions of water flows in National Forest System lands in northern Wyoming. Draft manuscript. U.S. Forest Service, Region 2, Denver, CO.

Rosgen, DL, HL Silvey, and JP Potyondy. 1986. The use of channel maintenance flow concepts in the Forest Service. American Institute of Hydrology, *Hydrological Science and Technology: Short papers* 2(1):19-26.

Ryan, SE, and CA Troendle. 1996. Bedload transport patterns in coarse-grained channels under varying conditions of flow. In: Proceedings of the 6th Inter-agency Sedimentation Conference, Las Vegas, Nevada, March 10-14, p. VI-22 to VI-27b.

Ryan, SE, and WW Emmett. 2002. The nature of flow and sediment movement in Little Granite Creek near Bondurant, Wyoming. Gen. Tech. Rep. RMRS-GTR-90. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station, 48 p.

Ryan, SE, LS Porth, CA Troendle. 2002. Phases of bedload transport defined using piecewise regression. *Earth Surface Processes* 27:971-990.

Ryan, SE, LS Porth, CA Troendle. 2005. Coarse sediment transport in mountain streams in Colorado and Wyoming, USA. *Earth Surface Processes and Landforms* 30(3):269-288.

Schmidt, LJ, and JP Potyondy P. 2004. Quantifying channel maintenance instream flows: an approach for gravel-bed streams in the Western United States. Gen. Tech. Rep. RMRS-GTR-128. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station, 33 p.

Stromberg, JC, DT Patten. 1996. Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. *Regulated Rivers: Research and Management* 12:1-12.

Stromberg, JC, DT Patten, and BD Richter. 1991. Flood flows and dynamics of Sonoran riparian forests. *Rivers* 2(3):221-235.

Trush, WJ, SM McBain, and LB Leopold. 2000. Attributes of an alluvial river and their relation to water policy and management. *Proc. Natl. Academy of Science* 97(22): 11858-11863.

USDA Forest Service 1985. Water information management system handbook. FSH 2509.17, Chapter 30, Procedure for quantifying channel maintenance flows, Washington, D.C.

Warburton, J. 1992. Observations of bed load transport and channel bed changes in a proglacial mountain stream. *Arctic and Alpine Research* 24(3):195-203.

Wathen, SJ, RI Ferguson, TB Hoey, and A Werritty. 1995. Unequal mobility of gravel and sand in weakly bimodal river sediments. *Water Resources Research* 31:2087-2096.

Whitaker, AC. 1997. The initiation of coarse bed load transport in gravel bed streams. Ph.D. Thesis, University of Montana.

Whiting, PJ, and JG King. 2003. Surface particle sizes on armoured gravel streambeds: effects of supply and hydraulics. *Earth Surface Processes and Landforms* 28:1459-1471.

Whiting, PJ, JF Stamm, DB Moog,and RL Orndorff. 1999. Sediment-transporting flows in headwater streams. *GSA Bulletin* 111(3): 450-466.

Wilcock, PR, and BW McArdell. 1997. Partial transport of a sand/gravel sediment. *Water Resources Research* 33(1):235-245.

Witte, LG. 2001. Still no water for the woods. American Law Institute-American Bar Association Federal Lands Law Conference, Oct. 19, 2001, Salt Lake City, UT, 21 p.

Wolman, MG, and JP Miller. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68:54-74.