Forest Service Channel Maintenance Flows in the Klamath Basin

Michael L. McNamara
Wallowa-Whitman National Forest, Baker City, Oregon

Tim Sullivan
USDA Forest Service, Northern Region, Missoula, Montana

The Fremont-Winema National Forest has filed channel maintenance in-stream flow water rights claims within the Upper Klamath River basin, Oregon. Claims were filed at 31 sites under the 1897 Organic Act, and represent an estimate of the minimum flows necessary to maintain stream channels over time. Data were collected on stream hydrology, the composition of bed-material, bedload transport over a range of flows, and channel characteristics. These data were used to formulate an instream flow claim based on the ability of the stream to move the larger particle sizes composing the streambed and banks, and thereby maintain the channel. Channel maintenance flows were determined to begin when the framework component of the bed-material as determined by the Parker-Klingeman bedload transport model began to be mobilized by the stream. Streambed framework materials consist of gravel-sized particles, and make up the major morphological features of the streambed. Channel maintenance flows are relatively high flow events, and include the range of high but not extreme discharges that are most effective at transporting bedload sediment and thereby maintaining channel capacity. Because this method for quantification of channel maintenance flow claims is calibrated to individual stream characteristics, it can be easily adapted for use in a wide variety of streams and conditions.

Keywords: *channel maintenance flows, Upper Klamath River basin, Fremont-Winema National Forest, Organic Act, bedload*

Introduction

Favorable Conditions of Flow and Reserved Water Rights

The Forest Service has filed Favorable Conditions of Flow (FCF) claims at 31 sites under the 1897 Organic Administration Act, 16 U.S.C. § 475, which defined the purposes for which National Forests were originally created. In 1978, the United States Supreme Court (United States vs. New Mexico, 438 U.S. 696, 706-707) reaffirmed the idea that that one of the reasons the National Forests were established was for the purpose of "securing favorable conditions of water flows." Water rights claims for instream flows were prepared by the Fremont-Winema National Forest, and were initially submitted to the Oregon Department of Water Resources in April 1997. The purpose of this paper is to provide detailed information on the concepts and procedures used in developing Favorable Conditions of Flow (FCF) channel maintenance instream flow water rights claims by United States Department of Agriculture, Forest Service, on national forest lands within the Upper Klamath River basin, Oregon. These claims prescribe the minimum amount of streamflow necessary to maintain stream channels over time and thereby ensure the delivery of water to downstream users.

Since the passage of the Organic Act, engineers and natural scientists have become more knowledgeable about the hydrologic cycle and have gained a better understanding of the effect of forested lands on incoming precipitation, runoff patterns, evaporation, and transpiration. The phrase "favorable conditions of flows" has been interpreted to apply to forest management and the hydrologic cycle in the following two ways. First, the forest was thought of as a moderator of runoff and streamflow, where flood flows such as spring runoff were stored. It was generally recognized that forest cover might increase infiltration of precipitation into the ground, reducing runoff and flood peaks and eventually increasing low flow in streams. Secondly, it was important to protect forests and the integrity of stream channels for the conveyance of streamflow so that forest lands could contribute to a sustainable water supply to downstream users.

M Furniss, C Clifton, and K Ronnenberg, eds., 2007. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004*, PNW-GTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

If a stream channel has reduced capacity to convey water, flows are impeded, the risk of flooding is increased, and the efficiency of water delivery to downstream users is impaired. The FCF instream flow claims are intended to maintain the physical characteristics of the channel so that the ability of the channel to convey streamflow and sediment is maintained. These non-consumptive claims do not reduce the amount of streamflow available for downstream appropriators and other uses. They are initiated only during periods of high streamflow, and require the minimum amount of streamflow necessary to maintain proper functioning condition of streams by maintaining channel capacity and channel features so that the ability to pass natural flows is ensured.

Channel Maintenance

Channel maintenance and the morphology of channels depend on a complex set of watershed physical processes and factors related to stream hydrology and the transport of sediment. A certain quantity of streamflow is necessary to transport the sediment entering the channel and thereby maintain channel form. As well as removing sediments supplied to the channel, higher flows prevent the encroachment of vegetative growth in the channel (Reiser et al. 1989). The amount of streamflow needed to maintain the channel depends on the quantity and sizes of sediment entering the channel. A stream will adjust to streamflow and sediment inputs to maintain a mean equilibrium that reflects the prevailing flow and sediment regimes (Lane 1955; Rosgen et al. 1986).

To maintain a channel's shape, the volume of material transported into the channel reach must be conveyed through the reach over time. Failure to convey the sediment load delivered to a stream reach over time will result in sediment accumulations in the reach and reduction in the capacity to convey flood flows. Channel maintenance flows must account for fluctuations in flow and the quantity and characteristics of the sediment and other debris supplied to the channel. Channel maintenance processes act over time. While sediment may accumulate during one period of time, accumulated sediments are eventually removed. For example, erosion of streambanks or sediment influx from tributaries may locally increase bed elevations, leading to small-scale flooding and flow diversion, with sediments eventually transported and redistributed to downstream areas.

The frequency and duration of moderately higher streamflows, especially flows around bankfull and larger, are particularly important for controlling channel morphology (Hill et al. 1991). Bankfull flows are those flows that fill the channel up to the stage where the stream just begins to overflow into its floodplain. In gravel-bed streams, these relatively high flows result in significant rates of bedload transport (Beschta 1987), because bedload transport rates generally increase rapidly with increasing streamflow. Large floods are very effective at altering channel form as they are able to transport significant amounts of sediment. However, over longer periods of time large events transport a far smaller total volume of bedload (Leopold 1992). In contrast, flows that fill the channel to the level of the floodplain (bankfull flows) are most effective at moving sediment over time, and are the dominant channel-forming flows (Wolman and Miller 1960; Andrews 1984; Leopold 1992) in mobile, alluvial bed channels. The mean recurrence interval of bankfull flows (on an annual flood frequency series) for a large variety of rivers has been found to be about 1.5 years (Dunne and Leopold 1978), but can also vary considerably from the 1.5-year flood (Hey 1994).

Sediment Transport

The movement of sediment involves its entrainment, transport, and ultimate deposition. Bedload and suspended load are the two major modes of sediment transport (Graf 1971; Richards 1982). Suspended sediment consists mainly of finer particles such as silts and clays, which are completely supported by the turbulence of flowing water. Bedload usually consists of particles of sand, gravel, cobbles, and boulders that are transported by traction, or roll, slide, and bounce along the streambed.

In flowing water, the smallest particles such as silt, clay, and colloids are held in suspension within the water column. Suspended sediment concentrations typically show considerable variation over time, and respond in a non-linear and highly sensitive manner to changes in flow and sediment availability. Particle settling velocities and fluid forces in turbulent flow work to maintain larger particles such as sand in suspension. As a result, the distribution of sand of 0.01- to 1-mm diameter in the water column is not uniform, and often results in transport alternately as bedload and in suspension (Beschta 1987). The spatial concentrations of these larger particle sizes may continuously shift as flows encounter different channel geometries and hydraulic conditions in downstream transport.

Bedload transport rates in streams vary spatially and temporally, even during constant flow conditions. Generally, bedload transport increases rapidly with increasing discharge. That is, as discharge increases, bedload transport rates increase at an exponentially greater rate than the flow (Gomez 1991).

Importance of Bedload and Suspended Sediment to Channel Maintenance. Bedload is important in the formation of channels. Gomez (1991) points out that a significant portion of river-deposited sedimentary rocks in the geologic column are composed of particles coarser than the maximum sand size transported in suspension in contemporary river systems. Further, he states:

'If river morphology is viewed as the result of interplay between hydraulic conditions and the resistance of materials in the channel perimeter, bedload transport provides the major process linkage between these factors, and virtually all aspects of morphologic change in a river, including bank erosion, are governed by bedload transport.'

Movement of the coarser or larger bedload has been found to be more important in the formation of channel geomorphic features than the finer fraction of the bedload (Leopold 1992). The coarser fraction of the material transported by the stream annually, although it makes up a smaller fraction of the total bedload, determines and comprises the major features of the channel's morphology.

Suspended sediment may be important in channel-forming processes where it is a dominant component of the sediment supplied to the stream. In high energy gravel-bed streams, suspended sediment likely plays less of a role in channel maintenance than bedload. The finer fraction of suspended sediment (silts and clays) can often be transported very long distances within a river system [Fisk (1947), as cited in Chorley et al. (1984)], and may be transported through a reach without significant deposition.

In light of the dominant role of bedload in channel formation and maintenance, the methodology for determining FCF water rights claims should be based on bedload transport rates over a range of flows for a particular stream and the properties of the bed-material sediments to determine the appropriate flows needed to maintain channels. By determining the quantity and size of bedload transported with increasing discharge, a FCF instream flow claim can be established that asks for the smallest amount of streamflow necessary to accomplish the objectives of channel maintenance.

Estimation of Bedload Transport. Physical bedload prediction models are widely used to estimate bedload transport rates where extensive bedload samples and long-term flow information may not exist. These physically-based models rely on the premise that a unique relation exists between hydraulic variables, sedimentological parameters, and the rate at which bedload is transported. They use information including channel dimensions and profile, the size distribution and characteristics of bed-material, stream hydraulics, and energy slope, and bed shear stress (Vanoni 1978; Parker and Klingeman 1982; Dawdy and Vanoni 1986). Bedload transport equations generally assume equilibrium between bedload inflow and outflow. When applying a bedload transport equation, more accurate predictions can be obtained when the model is calibrated against field data from the particular site where it is to be applied (Dawdy and Vanoni 1986).

Bedload transport in the Upper Klamath basin was estimated by the Forest Service using the model developed by Parker and Klingeman (1982). This bedload transport model utilizes bed shear stress to estimate transport. Bed shear stress is measured as the force of flowing water against the bed, and is calculated based on the specific weight, depth and energy slope of the water. The Parker-Klingeman (PK) bedload transport model can be calibrated to the individual hydraulic, morphologic, and bedload transport characteristics of streams.

The subpavement particle size distribution was used as the basis for bedload transport modeling, because over time, the bedload composition more closely resembles the subpavement particle size distribution. Calibration of the model using locally derived hydraulic and bed-material characteristics should greatly enhance the predictive power of a bedload transport formula (Dietrich and Smith 1984). A more detailed description of the application of the PK model is described in Bakke et al. (1999).

Streambed Characteristics: The Nature of Bed Sediments

Adequate characterization of bed-material is a fundamental part of establishing Favorable Conditions of Flow instream flow claims, using the approach taken in the Klamath River basin by the Forest Service. Bed-material distributions are used in the bedload sediment transport modeling process, to characterize channel roughness, and to determine initiation of transport of bedload. Bedload initiation information obtained from bed-material sampling is important in the development of water rights claims for channel maintenance.

Bed-material in alluvial, gravel-bed rivers is often observed to be poorly sorted and spatially heterogeneous, and can include a large variety of size classes. This spatial heterogeneity is often more pronounced in streams and rivers in mountain environments. Differences in material sizes on the bed of a stream can be caused by a variety of processes including mass wasting inputs, glacial lag deposits, logs or other debris, tributary inflow, and the migration of channel bedforms. The specific geomorphic and geologic context of a stream will influence the patterns of sediment delivered to the stream, and ultimately its bed-material size distribution.

Bed-material is characterized by a bed surface layer that is often more coarse than the underlying material, especially in heterogeneous sediments (Chin et al. 1994). Below dams or in other areas of diminished sediment supply, this layer has been called a static armor layer (Gessler 1967; Little and Mayer 1976; Bray and Church 1980) and is relatively immobile at ordinary discharges. Mobile armor, in contrast, exists where an upstream sediment supply is present (Andrews and Parker 1987), and is mobile under frequently occurring high flows (Leopold and Rosgen 1991).

The mobile armour layer may also be described as pavement (Parker et al. 1982; Parker and Klingeman 1982), and is approximately equal in thickness to the depth of the larger exposed particles (Andrews and Parker 1987; Andrews and Erman 1986). The layer of generally finer bed-material lying below the pavement layer is called the subpavement layer (Parker and Klingeman 1982), or the sub-armour layer. This layer may act a source of sediment to replenish the surface layer as it erodes (Parker and Sutherland 1990). An understanding of the various processes by which the bed of the stream and the pavement and subpavement layers change with increasing flow is important for the application of bedload transport equations used to predict amounts and size classes of bedload at various flows (Dawdy and Vanoni 1986).

The pavement layer of the stream (Figure 1) has been described as being inherently mobile and dynamic, and interchanges with the bedload. It forms readily on streambeds, and has been found to be present even during floods capable of moving all available grain sizes (Parker and Klingeman 1982). It has also been described by Parker and Klingeman (1982) as being a regulator that forms "just so as to render all available grain sizes of nearly equal mobility." The pavement layer acts to hide the smaller sized bed-material from the flow, and limit its entrainment into the bedload. In turn, larger particles exposed on the bed surface are more exposed to flow, and as a result are nearly as mobile as the finer material (Parker and Klingeman 1982; Andrews and Parker 1987).

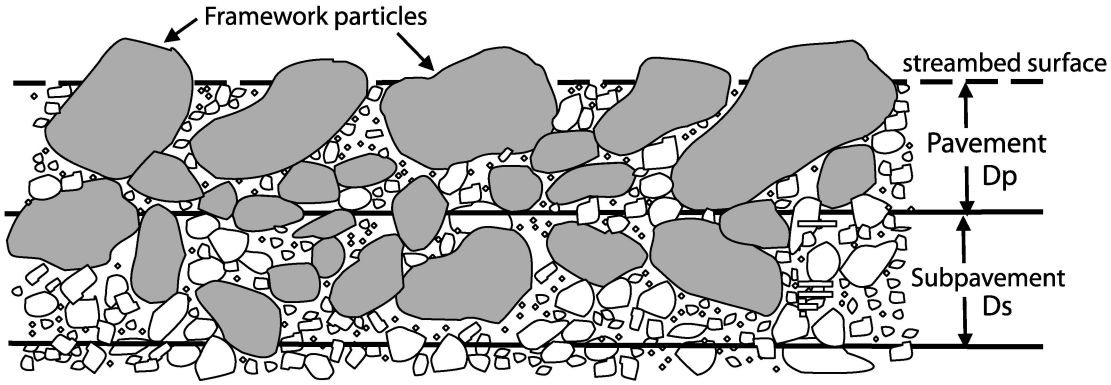
Gravel-bed, alluvial channels are composed of materials deposited by flowing water. In many alluvial rivers gravels deposited by the river consist of a framework of coarse particles or clasts, the voids of which are filled to some degree with finer sediments, which are termed the matrix materials (Miall 1996; Church et al. 1987; Carling and Reader 1982). Framework particles are usually in tangential contact with each other and form a stable, self-supporting structure (Pettijohn 1975). Deposits in which finer material such as sand and silt exceeds 30 percent of the total volume of sediment are called 'matrix supported' gravels. Large framework clasts in these deposits are not necessarily in contact with each other, and the spaces between large particles are filled with finer material.

Study Area, Channel Maintenance Sites and Data Collected

Physiogeographic Setting

The Upper Klamath River basin is located in south-central Oregon and northern California. It is bordered on the west by the summit of the Cascade Range, on the north by the Deschutes River basin, on the south by the Pitt River watershed, and on the east by the northwestern margin of the Great Basin. The geology is mostly volcanic, with minor accumulations of alluvium and other sedimentary strata. Precipitation varies from over 70 inches (178 cm) annually in the higher areas of the Cascades, to less than 20 inches (51 cm) annually in lower, more arid areas. The portion of the basin above Upper Klamath Lake is over 3000 mi^2 (7680 km^2) in area.

Figure 1. Alluvial gravel deposit, with pavement (Dp), and subpavement layer (Ds). Framework is shown by the darker particles. Matrix is composed of finer material between larger grains, and may consist of small gravel, sand, or finer material.



The Klamath River flows about three hundred miles (482 km) from its headwaters to the Pacific Ocean. Three major tributaries contribute to the flow of the Klamath River. These are the Sprague, the Sycan, and the Williamson, all of which arise in a mountainous region of south-central Oregon and drain into Upper Klamath Lake. The Klamath River itself begins where the river flows out of Upper Klamath Lake.

Sites and Data Collected

Thirty-one USDA Forest Service claim sites were included in the analysis of channel maintenance flows. These channel maintenance sites were located on alluvial channels within the boundaries of the Winema, Fremont, and Klamath National Forests, and were usually located near the national forest boundary. All flow and bedload information was collected at a claim site consisting of a specifically designated cross section, termed the channel maintenance cross section. Selection of the location of this cross-section followed guidelines outlined in Rantz (1982). Information on bedload transport, bed-material, stream discharge, and water surface slope data were collected at all claim sites.

More intensive bedload sampling and discharge measurements were done at ten fluvial process study claim sites (Table 1) to help further understand fluvial processes in the Upper Klamath River basin. These sites were selected because they were located in diverse geomorphic settings, which were thought to represent a variety of hydrologic and geomorphic conditions typically encountered in the Upper Klamath River basin. Information on sediment transport and discharge at these sites increased our understanding of fluvial process in the Upper Klamath River basin. The number of bedload samples at these locations varied from 5 to 26, however all but one fluvial site had more than 11 samples collected. Forest Service personnel collected all bedload samples with the single exception of the Sprague River at Chiloquin, Oregon site, where the US Geological Survey (USGS) collected the bed-material. Two of the streamflow gages were run by other agencies, and had substantially longer periods of record than the Forest Service gages, which ran for 5 to 7 years. All streamflow gages at these sites were recording gages.

Bedload transport samples were collected at 21 miscellaneous sites. Real time stream gages were operated at 10 of these sites. Discharge was measured approximately monthly during the spring, summer, and fall months at the remaining 11 ungaged sites. From two to four bedload samples were collected at each of these sites.

Methods

Discharge Measurements and Rating Curves. Discharge measurements were performed and discharge rating curves developed for each site using methods established by the Water Resources Division of the USGS, as outlined in Rantz (1982). Discharge records were adjusted to accommodate shifts in channel controls and bed elevations, and to accommodate ice blockage in the channels during the winter and spring months. Flow duration curves were generated from processed stream data. At sites with data recorders, pressure transducers were used to record hourly water stage. Transducers were housed in a stilling well located near the cross section used for discharge measurements.

Bed-material Sampling. Given the broad spectrum of particle size classes often encountered in gravel-bed rivers, it is difficult to design and implement a sampling program that adequately represents all or most of the material present. Changes in substrate size and condition can vary longitudinally, laterally, and over time. The volume and area of the bed that was sampled must represent the bed-materials well enough to be used in the bedload

Table 1. Fluvial Process Sites, number of bedload samples collected, and period of record for discharge records used for claims.

Fluvial Process Site	Bedload samples collected	Flow data period of record	Number of years of flow record
Annie Creek	20	1991-1999	9
Cherry Creek	26	1993-1999	7
Fivemile Creek	12	1993-1999	7
N. Fk. Sprague River Sandhill	13	1993-1999	7
Paradise Creek	12	1993-1999	7
S. Fk. Sprague River Brownsworth	13	1993-1999	7
Sprague River Chiloquin	5	1921-1999	59
Spencer Creek	21	1993-1999	7
Sycan River above marsh	16	1993-1999	7
Williamson River Sheep Creek	11	1978-1999	22

transport model and in the calculation of framework bed particles. Our objective was to determine bed-material characteristics in the vicinity of the cross-section used for bedload transport estimates and flow measurements.

A fundamental aspect of accounting for the spatial and temporal variability of bed-material samples is the selection of a sample site. Bed-material samples generally were taken a short distance upstream or downstream of the bedload sampling cross section within the same hydraulic control as the cross-section. If this was impractical, samples were taken in a location with thalweg bed-material characteristics similar to the channel maintenance cross section. For most sites several bed-material samples were collected.

Volumetric samples of bed-material were collected after the methods of Milhous et al. (1995) using a barrel sampler, consisting of an open-ended and shortened steel drum. For most streams a 55-gallon (208-L) barrel sampler was used (diameter 58 cm). However, for streams with bed-material consisting of cobbles, pebbles, and sand sized particles, a 10-gallon (37.8-L) barrel sampler was used (diameter 27 cm). Since most of our streams were relatively shallow, the barrel sampler was generally effective. However, there were concerns regarding the adequate capture of fine material while using the sampler. Polyethylene tarp skirting was used as a flow barrier around the base of the barrel while sampling to prevent currents from washing fine material out of the sample.

The pavement layer depth was defined by the vertically oriented embedded depth of the largest particle exposed within the area of the streambed contained within the barrel sampler. Embedded depth was equal to the distance in the vertical direction of the most deeply embedded exposed particle to the surface of the matrix material (Figure 2). After the pavement layer was removed, subpavement samples were taken to a depth equal to the embedded depth of the pavement layer.

It was common for unequal total volumes of pavement and subpavement to be collected at each site, due to the fact that the pavement depth was measured into the channel bed from the plane of embeddedness. Larger particles embedded in the pavement layer protrude past the plane of embeddedness a short distance, and this increases the volume of the sample collected by an amount equal to the volume of the pavement particles that extend beyond the plane of embeddedness. Thus, in order to compare pavement with subpavement in each size class, proportions by weight were determined for each particle size class.

Bedload Sampling. Bedload sampling must account for spatial and temporal variation in bedload transport rates in order to adequately characterize mean bedload transport rates across a channel cross section at a given flow. Samples were taken at all sites with a 3-inch (7.62-cm) Helley-Smith sampler (Helley and Smith 1971) using methods outlined in Emmett (1981), Klingeman and Emmett (1982), and Edwards and Glysson (1988). The Helley-Smith sampler is a pressure difference bedload sampler developed specifically for use in gravel bed rivers. The hydraulic efficiency of the Helley-Smith sampler is 1.54. This sampler gives adequate information on the amount and sizes of bedload in transport, however since the sampler has a 3 x 3 inch (7.62 x 7.62 cm) opening, there is an upper limit to the sizes of material that it will collect. Sampling at all sites was done at ten equally-spaced points across the channel maintenance cross section, and the sampler was in place for 1 minute at each sampling point. For most samples four passes were made across the stream, thus giving total sample time of 40 minutes. This sampling time was thought to adequately account for temporal variability in bedload transport. Sampling was occasionally done near the upper limits of applicability of a handheld Helley-Smith sampler because of deep water and high flows. At some sites because of high flows and high bedload transport rates, the sampling times were reduced to 15-30 seconds at each vertical point. Sample times were altered because adequate sample volume was collected by the sampler in the shorter amount of time. When at-a-point sample times were reduced, total sample times were reduced correspondingly, since only four passes were made across the stream. Thus total sample times for a single bedload sample ranged from 10 to 40 minutes.

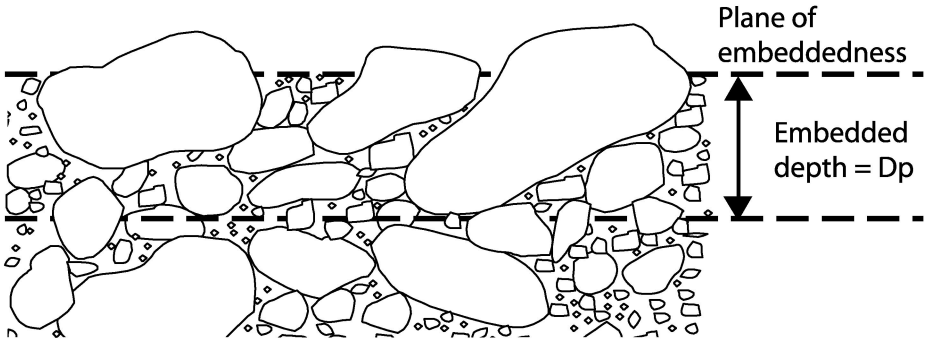


Figure 2. Pavement depth (Dp) is equivalent to the vertically oriented embedded depth of the largest exposed particle contained within the barrel sampler. Finer material between larger grains is matrix material.

Laboratory Analysis. Bed-material and bedload samples were dry sieved and weighed in the laboratory. Particles with a median diameter, or b-axis larger than 63 mm were weighed individually and their median diameter determined in the field. The sieve sizes used for bed-material analysis ranged from 0.063 to 64 mm. Sieve sizes used for bedload analysis ranged from 0.25 to 64 mm. Sizes below 0.25 were assumed to consist predominantly of particles transported in suspension.

Water Surface Slope and Cross-Sections. Longitudinal profiles of water surface slope and detailed surveys of the channel cross-sectional profile at the sampling cross section were needed to adequately characterize energy conditions and channel shape at the sampling location. To facilitate this, a permanent benchmark was established at each site, and this was used to determine relative water surface elevations up-and downstream of the sampling cross-section.

A tripod-mounted level was used to determine water surface elevation and bed surface longitudinal profiles and cross-sections at each bedload sampling site. Water surface slope is a good surrogate for energy slope, which is important for estimating the stream power available for bedload transport. Surveys were done adjacent to the streambank upstream and downstream of the bedload sampling cross-section. The elevation of the water surface was determined at closely spaced intervals. Interval length was dependent on the size of the stream and the complexity of the channel. Generally, elevation intervals were more closely spaced for smaller, higher gradient streams, and wider for larger, less steep streams and rivers. Longitudinal profiles were used to determine water surface slope in the immediate vicinity of the sampling cross-section, usually from the upstream to downstream channel controls. A linear regression was applied to the slope survey points, and the median surveyed slope was selected as the representative slope. Several detailed surveys were done of each channel maintenance cross section. Survey points were spaced at relatively close intervals. Particular attention was paid to documenting breaks in slope or high and low points in the channel cross section.

Determining the Claim Initiation Discharge

The Forest Service claims were initiated when the framework component of the bed-material particle sizes began to be mobilized, as determined by the Parker and Klingeman (1982) bedload transport model. The process for determination of each FCF claim involves several steps:

1. Develop site stage/discharge rating curve and hydrograph
2. Determine stream bed-material and channel characteristics
3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

This procedure was used at all FCF claim sites. The following is an example of the process and data used for determining the minimum flow needed to begin mobilizing the framework material for a fluvial process site.

Develop Site Stage/Discharge Rating Curve and Hydrograph

The South Fork of the Sprague River fluvial process site is located at the outlet of a 62.1 square miles (161 km^2) mostly forested watershed at an elevation of 4540 ft (1384 m), just upstream of the confluence with Brownsworth Creek. The geology is almost exclusively volcanic, with minor accumulations of alluvium near streams. Normal precipitation in the watershed ranges from about 40 inches (~102 cm) per year at the highest elevations to about 20 inches (~51 cm) per year near the gage (Oregon Climate Service 1992).

The South Fork of the Sprague River gage has operated from water year 1993 to the present. Discharge records from 1993-1998 were used for developing the FCF claims. A data logger instrumented with a pressure transducer was used to record stage, and observations of stage were made at 30-minute intervals. A stage vs. discharge rating curve was developed (Rantz 1982), and this was used to generate a mean daily hydrograph for the period of record. The hydrograph was inspected for periods of ice blockage of the channel, and mean daily hydrographs from nearby ice-free gages from the same period were used to adjust the hydrograph. Flow records were used to generate a flow duration curve (Dunne and Leopold 1978) representing the water years 1993-98.

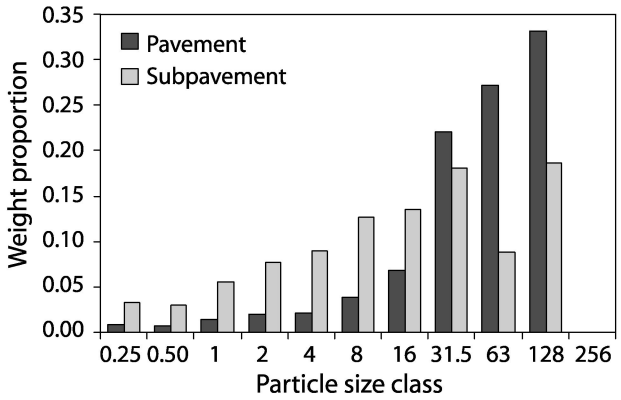
Determine Stream Bed-material and Channel Characteristics

Bed-material data were used to generate size distributions for both the pavement and subpavement layers. Cumulative distributions were used to generate median particle diameters (D_{50}) and the 84th percentile (D_{84}) for the bed-material (Figure 3).

Weight proportions of bed-material in each particle size class were then determined. Usually several samples

of both pavement and subpavement were collected. To calculate the proportions of material in each particle size class, weights of different samples in each size class were added and the proportions calculated from the weight totals in each size class.

Figure 3. Bed-material distribution of pavement and subpavement, S. Fork Sprague River.



Model and Predict Bedload Transport over a Range of Flows

The Parker-Klingeman (PK) model uses bed shear stress to estimate bedload transport. A more detailed description of the application of the PK model is described in Bakke et al. (1999). The procedure consists of calibrating two empirical constants (an exponent and a reference Shield's stress) using site-specific information, including two or more bedload measurements, bed-material and channel cross-section characteristics, and water surface slope. The PK equation can be calibrated for a wide set of conditions. A program called SEDCOMP (Dawdy 1997) was used to optimize the bedload transport equation, and calibrate it to site specific information on bedload transport at each claim site. A separate program FLOWDUR (Dawdy 1997) uses the calibrated parameters and optimized PK equation developed in SEDCOMP combined with an estimated flow duration curve and bedload rating curves to compute thresholds for bedload transport of different size classes of material.

Develop Framework Bed-material Size Distribution

Mobilization of particle size classes consisting of framework particles is essential for maintaining channel morphology. These particle size classes represent the size fractions which, when mobilized, maintain channel form over time. These materials consist of gravel-sized particles, and make up the major morphological features of the streambed (Leopold 1992). The bed-material framework particles for this study were determined through analysis of bed-material samples that were collected at each bedload sampling location.

As was mentioned earlier in this paper, the pavement layer of the stream-bed is generally coarser than the underlying subpavement layer. The first step in identifying the framework particles is to calculate the weight proportions in each particle size within the pavement and subpavement layers. The framework gravels are determined by subtracting the weight proportion in each size class of subpavement from the respective proportion in each size class in the pavement. This procedure determines the bed-material size classes of the pavement layer that generally have a higher proportion by weight than the material found within those size classes in the subpavement layer. These materials are the framework gravels.

Table 2 provides an example of the calculations used to determine this distribution. The weight proportions of subpavement are subtracted from the corresponding proportions of pavement. Weight proportions were used

Figure 4. Application of the Parker-Klingeman bedload transport model.

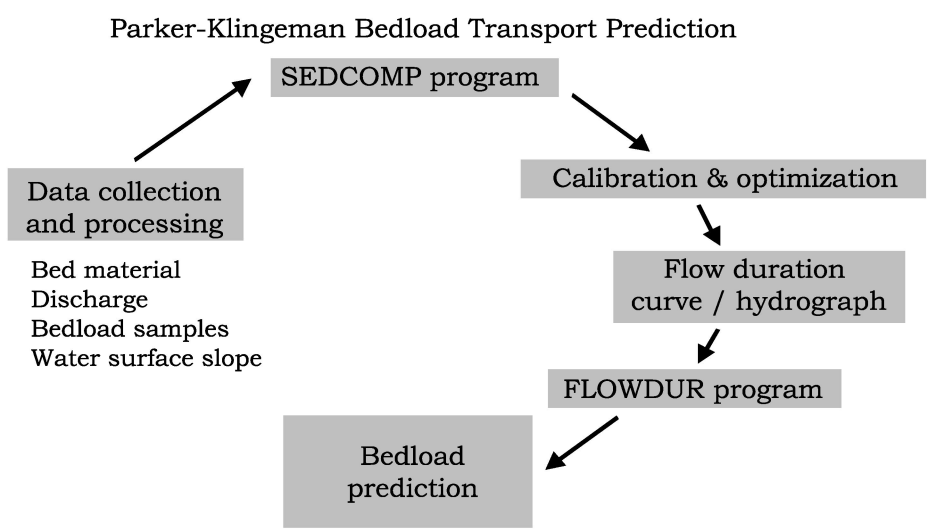


Table 2. Weight proportions of bed material and determining the framework particle size distribution, S. Fork Sprague River. Proportions of subpavement are subtracted from the pavement to obtain the framework distribution. In this example the framework is from 32 to 126 mm.

	Particle Size (greater than, mm)										
Layer	**0.25**	**0.50**	**1**	**2**	**4**	**8**	**16**	**31.5**	**63**	**126**	**253**
Pavement	0.008	0.008	0.014	0.019	0.022	0.038	0.068	0.220	0.271	0.331	0
Subpavement	0.032	0.029	0.055	0.077	0.089	0.127	0.136	0.180	0.088	0.187	0
Framework (pavement - subpavement)	< 0	< 0	< 0	< 0	< 0	< 0	< 0	0.040	0.184	0.144	0

because unequal volumes of material were collected in each layer of bed-material. The volume is different between the layers because the pavement depth is determined by the embedded depth of the largest exposed particle. The framework size distribution was determined for the South Fork Sprague River, and is combined with the pavement and subpavement distributions in Figure 5.

The calculated framework distribution for this example ranges from 31.5 to 126 mm in size. The lower limit of the FCF claim begins when the framework distribution of the bed material begins to be mobilized.

Determine Lower and Upper Limits of Flow

Bedload transport model results can be used to determine the lowest discharge at which a particular particle size class shows appreciable movement. The bedload transport quantities and sizes per unit discharge are quantified by discharge increment, and the relative amount of transport for each particle size class is determined.

Moving framework particles is essential for channel maintenance. The instream flow claim initiates at the flow where 2% of the total bedload by weight is composed of framework particles. This percentage was selected based on comparative observational analysis of bedload transport rates at all claim sites. On average at all the claim sites, these claim initiation flows, based on the mobilization of framework particles, corresponded to about 60% of bankfull flow.

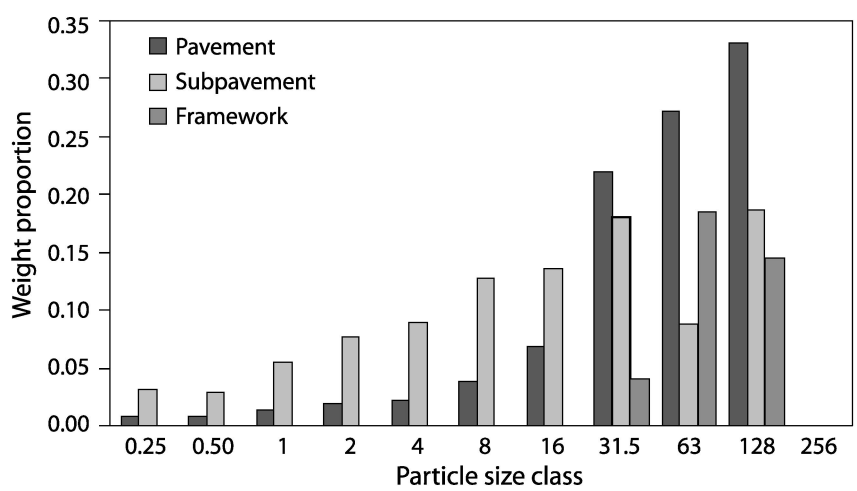
The 25-year flood event calculated using regional flood frequency estimates (Harris et al. 1982) was selected as the upper limit for the claim, because it represented a reasonable upper limit for the channel maintenance claims. These estimates were customized to conditions in the Klamath River basin by EA Engineering (unpublished report 1987).

Final Claim Structure

South Fork Sprague River Example

An example of the application of a Favorable Condition of Flow water rights claim for the period 1993-98 is shown in Figure 6. The claim is shown by the shaded region of a mean daily hydrograph for this location. At South Fork Sprague River the instream flow initiates at the claim initiation water flow (140 cfs [3.96 cubic meters per second {cms}]), and is capped at the 25-year event at 926 cfs (26.2 cms). For most years, water is claimed predominantly during higher flows during the late winter and spring months. Water year 1994 was the driest year

Figure 5. Framework distribution with pavement and subpavement, South Fork Sprague River.



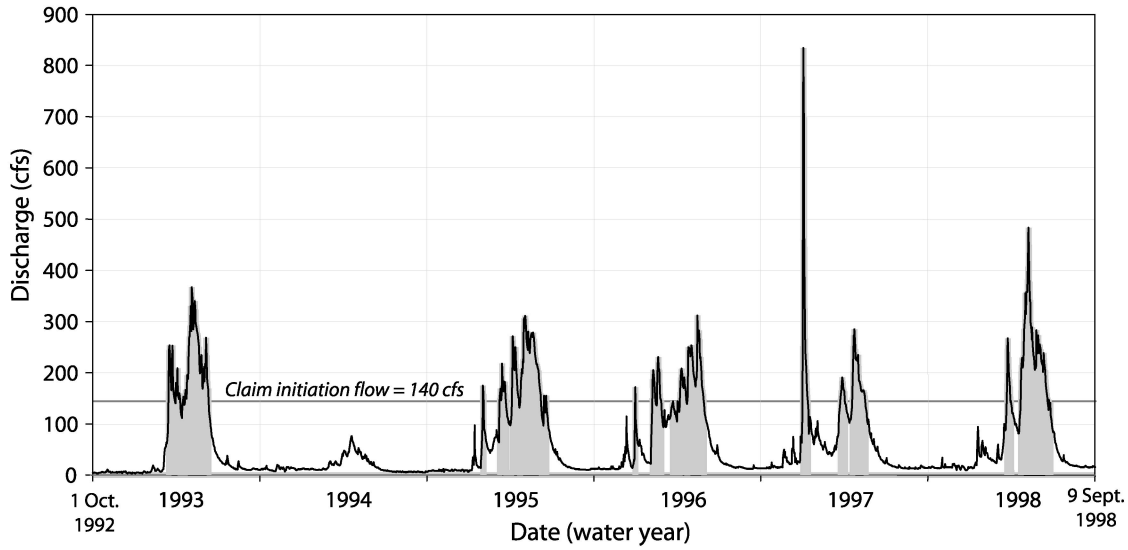


Figure 6. Mean daily hydrographs from South Fork Sprague River for water years 1993-1998. Favorable conditions of flow claims are the shaded areas of the hydrograph.

since this site has been gaged, and streamflow remained below the claim initiation flow for the entire water year.

Discussion

An examination of the hydrographs in Figure 6 reveals that the FCF instream flow claims consist of a series of peak flows with the bulk of the discharge occurring during spring snowmelt runoff. The runoff increases in December and January of 1995 and 1996 are probably early season rain-on-snow peak flows. April through July runoff in water years 1993-1996 for an Upper Klamath River basin gage as percent of average is summarized in Table 3. These data were compiled for the USGS-operated gage on the Sprague River at Chiloquin. The driest year on record was 1994, with runoff predicted at 32% of average. In contrast, 1993 was a very wet year, with runoff predicted at 129% of average. In 1995-96, runoff was at near normal levels. To the extent that the estimate of streamflow at the USGS gage represents conditions at the South Fork Sprague gage, the hydrographs for the years 1995 and 1996 probably are typical of the percent of water claimed during near average projected runoff years. However, the timing of spring runoff and the resulting claim may vary from year to year, despite any similarities in runoff volume.

Table 3. Percent of average runoff, Klamath River basin, Sprague River at Chiloquin gage.

Year	Percent of Average Runoff
1993	129
1994	32
1995	90
1996	99

Inspection of the hydrographs (Figure 6) also reveals that most of the water volume claimed for FCF in-stream claims occurs during the spring months when potential and existing agricultural irrigation withdrawals are at a minimum. During the period July through September, no water would have been claimed for FCF claims. Exercise of FCF in 1993 and 1994 would have ended in mid-June, and in May of the 1996 water year. It is also important to note that this claim site is located on Forest Service managed public lands in an area where no agricultural activities exist or are likely to occur. However, diversions from the South Fork of the Sprague occur several miles below this location in the upper Sprague River valley.

Summary and Conclusions

Favorable Conditions of Flow (FCF) in-stream flow claims were developed using extensive knowledge of site hydrology, geomorphology, the sizes and character of streambed-materials, combined with information about the transport of bedload by the stream. They are based on the premise that a certain quantity of streamflow is necessary to transport inputs of sediment to the channel and thereby maintain the channel's form and its ability to convey streamflow and sediment. The claims were developed in five steps. These were:

1. Develop site rating curve and hydrograph
2. Determine stream bed-material and channel characteristics

3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

The FCF instream claims are initiated during relatively high flow events. The lower limit of these claims is determined by the characteristics of the material composing the streambed and the results of bedload sediment modeling. Instream flows are capped by the 25-year flood. The frequency and duration of these higher streamflows are important for controlling channel form and dimensions. The resulting instream flow encompasses the range of discharges that are most effective at conveying bedload sediment and thereby maintaining channel capacity. In light of the dominant role of bedload in channel formation and maintenance, this method uses bedload transport rates over the range of flows observed at a particular stream and the properties of the bed-material sediments to determine appropriate FCF streamflows needed to maintain channels. Further, because bedload transport rates increase rapidly with increasing discharge, and because higher discharges occur relatively infrequently, a high percentage of the bedload can be moved by a relatively small volume of streamflow-the minimum amount of flow necessary to maintain the channel.

Literature Cited

Andrews, ED. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Geol. Soc. Am. Bull.* 95: 371-378.

Andrews, ED, and DC Erman. 1986. Persistence in the size distribution of surficial bed-material during an extreme snowmelt flood. *Water Resources Research* 22(2):191-197.

Andrews, ED, and G Parker. 1987. Formation of a coarse surface layer as the response to gravel mobility. In: C.R. Thorne, J.C. Bathurst, and R.D. Hey (eds), Sediment transport in gravel-bed rivers, Chichester, UK: John Wiley and Sons: 269-325

Bakke, PD, PO Basdekas, DR Dawdy, and PC Klingeman. 1999. Calibrated Parker-Klingeman model for gravel transport. *Journal of Hydraulic Engineering ASCE* 125(6):657-660 .

Beschta, RL, 1987. Conceptual models of sediment transport in streams. In: CR Thorne, JC Bathurst, and RD Hey (editors), Sediment transport in gravel-bed rivers, Chichester, UK: John Wiley and Sons: 387-408.

Bray, DI and M Church. 1980. Armored versus paved gravel beds. *Proc. Am. Soc. Civ. Engrs., J. Hydraul. Div.* 91(HY4): 225-247.

Carling, PA, and NA Reader. 1982. Structure, composition, and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms* 7:349-365.

Chin, CO, BW Melville, and AJ Raudkivi. 1994. Streambed armoring. *Journal of Hydraulic Engineering* 120(8):

Chorley, RJ, SA Schumm, and DE Sugden. 1984. Geomorphology. New York: Methuen & Co, 605 p.

Church, MA, McLean, DG, and JF Wolcott. 1987. River bed gravels: Sampling and analysis. In: CR Thorne, JC Bathurst, and RD Hey (editors), Sediment transport in gravel-bed rivers, Chichester, UK: John Wiley and Sons: 43-87.

Dawdy, D. 1997. SEDCOMP and FLOWDUR, sediment computation using the Parker Klingeman method. Western Hydrologic Systems, Auburn, CA.

Dawdy, D, and VA Vanoni. 1986. Modeling alluvial channels. *Water Resources Research* 22(9):71-81.

Dietrich, WE, and JD Smith. 1984. Bedload transport in a river meander. *Water Resources Research* 20:1355-1380.

Dunne, T, and LB Leopold. 1978. Water in environmental planning. San Francisco, CA: W.B. Freeman and Company.

Edwards, TK, and DG Glysson.. 1988. Field methods for the measurement of fluvial sediment. U.S. Geological Survey Open File Report 86-531, 117 p.

Emmett, WW. 1981. A field calibration of the sediment trapping characteristics of the Helley-Smith bedload sampler. U.S. Geological Survey Prof. Paper No 1139, 44 p.

Fisk, HN, 1947. Fine-grained alluvial deposits and their effect on Mississippi River activity, Vicksburg, Miss., U.S. Corps of Engineers, Mississippi River Commission, Waterways Experiment Station, 2 vols.

Gessler, J. 1967. The beginning of bedload movement of mixtures investigated as natural armoring in channels (translated by EA Prych, California Institute of Technology), Swiss Federal Institute of Technology, Zurich, Laboratory of Hydraulic Research and Soil Mechanics, Rept. No. 69, 89 p.

Gomez, B. 1991. Bedload transport. *Earth Science Reviews* 31:81-132.

Graf, WH. 1971. Hydraulics of sediment transport. New York: McGraw-Hill, 513 pp.

Harris, DD, LL Hubbard, and LE Hubbard. 1982. Magnitude and frequency of floods in eastern Oregon. U.S. Geological Survey Open File Report 79-553. 35 p.

Helley, EJ, and W Smith. 1971. Development and calibration of a pressure difference sampler. U.S.Geological Survey Open File Report.

Hey, RD. 1994. Channel response and channel forming discharge: Literature review and interpretation. First interim report of contract number R.D. 6871-EN-01, 60 p.

Hill MT, WS Platts, and RL Beschta. 1991. Ecological and geomorphological concepts for in-stream and out-of-channel flow requirements. *Rivers* 2(3):198-210.

Klingeman, PC, and WW Emmett. 1982. Gravel bedload transport processes. In: RD Hey, JCBathurst, and CR Thorne (eds). Gravel-bed rivers, New York: Wiley and Sons: 141-179.

Lane, EW. 1955. The importance of fluvial morphology in hydraulic engineering. *American Soc. Of Civ. Eng. Proceedings, Hyd. Div.* 81:745-1 to 745-17.

Leopold, LB. 1992. Sediment size that determines channel morphology. In: P Billi, RD Hey, CR Thorne, and PTaconi (editors), Dynamics of gravel-bed rivers, Chichester, UK: John Wiley and Sons: 297-310.

Leopold, LB, and DC Rosgen. 1991. Movement of bed-material clasts in mountain streams. Proceedings of the Fifth Interagency Sedimentation Conference, Las Vegas, Nevada, pp. 183-187.

Little, WC, and PG Mayer. 1976. Stability of channel beds by armoring. Proc. Am. Soc. Civ. Engrs. J. Hydraul. Div. 102(HY11), 1647-1661.

Miall, AD. 1996. The geology of fluvial deposits. New York: Springer: 98-108.

Milhous, RT, SA Hogan, SR Abt, and CC Watson. 1995. Sampling river-bed materials: the barrel sampler. Rivers 5: 239-249.

Oregon Climate Service. 1992. Normal annual precipitation, State of Oregon, 1961-1990.

Parker, P, and PC Klingeman. 1982. On why gravel bed streams are paved. Water Resources Research 18(5):1409-1423.

Parker, G, and AJ Sutherland. 1990. Fluvial armor. *Journal of Hydraulic Research* 28(5):529-544.

Parker, G, SD Dhamotharan, and H Stefan. 1982. Model experiments on mobile, paved gravel bed streams. *Water Resources Research* 18(5):1395-1408.

Pettijohn, EJ. 1975. Sedimentary rocks. 3rd Edition, New York: Harper International, 628 pp.

Rantz, SE. 1982. Measurement and computation of streamflow: Volume2. Computation of cischarge. USGS Water Supply Paper 2175. 284 p.

Reiser, DW, MP Ramey, and TA Weche. 1989. Flushing flows. In: JA Gore and GE Petts (eds), Alternatives to regulated flow management, Boca Raton, LA: CRC Press: 91-135.

Richards, K. 1982. Rivers: Form and process in alluvial channels. London: Methuen, 358 p.

Rosgen, DL, HS Silvey, and JP Potyondy. 1986. The use of channel maintenance flow concepts in the Forest Service. Hydrological Science and Technology: Short Papers, Amer. Inst. Hydrol. 2(1):19-26.

Vanoni, VA. 1978. Predicting sediment discharge in alluvial channels. *Water Supply Management* 1:399-417.

Wolman, MG, and JP Miller. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68(1):54-74.