Gravel-Bed River Behavior: Some Comments on Bedload, Dams, and the Deschutes River

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INTRODUCTION

The Pelton-Round Butte dam complex on the Deschutes River near Madras, Oregon, is operated as a hydroelectric project by Portland General Electric (PGE). As part of the Federal Energy Regulatory Commission relicensing process, PGE funded studies by scientists of the U.S. Forest Service (USFS), U. S. Geological Survey (USGS), and Oregon State University (OSU) to evaluate the effects of the dam complex on the geomorphology of the Deschutes River below the complex. The reports from these studies, two OSU Master's theses (Fassnacht, 1998; McClure, 1998) and two summary reports (Grant and others, 1999; O'Connor and others, 1999), provide a wealth of information ranging from the ancestral history of the river to details of bed-material particle sizes of the Deschutes River. The writer was contracted by PGE to review these reports, to assess the adequacy of the geomorphic studies, and to make recommendations for any needed additional studies or monitoring into the future.

I met, both in the field and in the office, with the senior authors of the geomorphic studies, with hydrologists from the USFS and the Bureau of Land Management (BLM), and with PGE personnel. These meetings included reconnaissance of much of the drainage area upstream of the dam complex, floating nearly 20 miles of the Deschutes River immediately downstream of the dam complex, and reconnaissance by road of the Deschutes River between Madras and Maupin, Oregon.

The conclusions from the reports generated by the geomorphic studies indicate that recent hydraulic- and channel-geometry characteristics have been consistently steady with time, and that the effects of the dam complex on these characteristics have been minimal. My field observations of the Deschutes River showed no evidence that these conclusions of the studies are not accurate. However, measurements of some fluvial processes describing bed mobility are difficult to obtain. Observations of scour and fill generally involve comparison of streambed elevation between times of high and low flows; measurement of bedload transport requires skilled personnel and specialized equipment and is most relevant during the small percentage of time of highest flow. Largely for these reasons, the geomorphic studies did not emphasize seasonal scour and fill, and bedload-transport rates were modeled rather than measured. Modeled bedload-transport rates on the Deschutes River indicated less frequent occurrence of bedload transport than do measured bedload-transport rates on many other gravel-bed rivers. Because of this apparent discrepancy, I was asked by PGE to review the information and provide recommendations for possible future work.

The following pages provide comments on gravel-bed river behavior, characteristics of the Deschutes River, recommendations of additional studies, and a listing of relevant references. Importantly, the comments represent a common understanding from the field and office discussions.

GENERAL STATEMENT

Dams, especially those with large reservoir capacity, have the capability of altering fluvial processes. Specifically, they have the capability of disturbing the downstream conveyance of water and sediment. Because few dams have provisions for conveying sediment around the dam, the effect is often 100 percent blockage of sediment. And because dams are built with a purpose, the effect on streamflow reflects the operating policy of the dam; often the effect is attenuation of peak flows and enhancement of low flows. Where there is a complex of dams with capabilities of flow regulation, an operating policy can be developed in which final outflow mimics natural, and the effects on continuity of streamflow may be minimal to nonexistent.

Gravel-bed alluvial rivers are those whose beds are primarily composed of unconsolidated material with median sizes larger than sand (2 mm). Beds and banks are dominated by gravels and larger materials, and they often have an armor layer of coarser material covering the channel bed. Although suspended sediment usually constitutes more of the total sediment load of a river than bedload, it plays a less important role in determining channel morphology (Leopold, 1992). Bedload may vary from about 1 percent of total sediment load (Tanana River near Fairbanks, Alaska; in Emmett, 1984) to nearly half (East Fork River near Pinedale, Wyoming; from references in Leopold and Emmett, 1997). Typically for gravel-bed rivers, bedload is about 2 to 10 percent of total sediment load (Little Granite Creek near Bondurant, Wyoming; in Leopold, 1994).

The relation of bedload discharge to water discharge is such that a doubling of water discharge results in more than a doubling of bedload discharge. Stream competence, or the ability to move larger size particles, generally increases with increasing streamflow. Accordingly, high-flow discharges are most efficient in transporting bedload and may be required to move the larger particles.

Much of the bedload in typical gravel-bed rivers is sand and fine gravel, and usually is supply limited. This sediment is mobile over a large range of flows, moving atop the nonmoving coarser particles. The coarse sediment, which makes up much of the bed and which is mobile only during higher flows, is transport limited; that is, the supply is not limited but movement is controlled by the energy of the streamflow (adapted from Emmett, 1976). Streamflows capable of moving transport-limited material will also transport the supply-limited material.

Quantifying the streamflows required to move the coarse material defines channel-maintenance flows. Considerations of efficiency and competence require a quantification using the largest flows. Further, the movement of the coarse bed material provides the cleansing and resetting of the bed structure important to fishery habitat. Accordingly, quantification of habitat-maintenance flows for fishery resources often uses the same methodology as quantification for channel-maintenance flows.

Examples of such channel-maintenance quantification for gravel-bed rivers indicate the following:

(1) Little Granite Creek near Bondurant, Wyoming (drainage area = 21.1 mi^2, average annual discharge = 29.5 ft^3/s) requires 18 percent of the water and flows that occur 2 percent of the time (Emmett, 1999).

(2) Boise River near Twin Springs, Idaho (drainage area = 830 mi^2, average annual discharge = 1,200 ft^3/s) requires 30 percent of the water and flows that occur 6 percent of the time (Emmett, 1998).

Recurrence and duration studies indicate that high flows required for bedload transport occur most years, but not every year, and typically average a duration of about two to four weeks per year. Because bedload transport occurs only during the few days of highest flow each year, any attenuation in magnitude or duration of these high flows could significantly decrease the quantity of bedload transported. For the above examples of gravel-bed rivers, typically about 30 percent of the bedload occurred as supply-limited transport before the streambed was disturbed and supply limitations were relaxed. Conversely, about 70 percent of the bedload occurred during the relatively few days that the coarse particles comprising the framework of the streambed were mobile.

Measured bedload transport in gravel-bed rivers indicates that bedload occurs over only a portion of the streambed, most often as stringers of bedload, or as bedload sheets alternating in periods of motion or rest. Seldom do either maximum transport rates or maximum particle sizes occur at the deeper and faster portions of streamflow, but rather at midway of sloping surfaces such as point bars on the inside of bends or lateral bars along straight reaches. The spatial occurrence of bedload is variable for different water stages at the same reach as well as between reaches for the same stage. This complicates the design of a bedload-sampling program and casts suspicion on computational schemes to predict bedload transport.

DESCHUTES RIVER

Streamflow of the Deschutes River is remarkably steady, an early known fact (for example, Henshaw and others, 1914) and reiterated recently (Grant and others, 1999; O'Connor and others, 1999). Actual streamflows are compiled in the annual reports, *Water Resources Data of Oregon*, of the USGS. Much of the steadiness of flow relates to porous geology that allows groundwater storage and spring-fed streamflows.

The Pelton-Round Butte dam complex is a series of three dams with re-regulation capabilities and an operating policy such that there is minimal attenuation or enhancement of flood peaks. Quantification of inflows to the upstream reservoir (Lake Billy Chinook) of the dam complex is based on reservoir stage, and conversion from stage levels to streamflows allows modest discrepancies in lag time, the time that peaks occur downstream from the dam compared to the time streamflow peaks would occur in the absence of the dam.

McClure (1998) has described characteristics of bed material in the Deschutes River downstream of the dam complex. Although bedload has not been measured in the Deschutes River, Fassnacht (1998) has computed bedload-sediment discharge in the Deschutes River downstream of the dam complex. These computations are for general motion of non-supply limited bed material, that is, movement of substrate bed material after the coarser-particle bed surface has been disturbed. The bedload computations suggest that bedload transport in the Deschutes River is an infrequent event, occurring about 0.1 percent of the time or about 25 days in the 72-year record, 1925–1996.

Total sediment discharge into Lake Billy Chinook has been estimated based on a reservoir-sedimentation survey, and reported by Grant and others (1999) as about 30 tons/square mile/year. This sediment yield is comparable to some smaller values of sediment yield reported for several other regions of the United States (Leopold, 1994). If bedload is 5 to 10 percent of this total sediment, bedload yield is about 1.5 to 3 tons/square mile/year. By comparison, the annual bedload yield for 12 locations in the Snake River drainage of Idaho ranges from about 1.5 to 35 tons/square mile (Emmett, 1998). The computed tonnage of bedload downstream of the dam complex constitutes about 2 percent of the total sediment deposition in Lake Billy Chinook upstream of the dam complex.

Additional geomorphic studies, especially comparison of time sequences of aerial photography and channel cross sections, suggest that the plan and profile of the Deschutes River is very stable with time. In their final report on the geomorphology of the Deschutes River below the Pelton-Round Butte dam complex, O'Connor and others (1999) state: "The combination of: (1) a channel and valley bottom that is extremely resistent to modification, and (2) only minimal interruption of the flux of water, sediment, and wood by the Pelton Round Butte dam complex, has led to the present condition of few clear changes to the Deschutes River channel morphology that can be attributed to impoundment." In my review, I found no evidence to contradict this conclusion.

DISCUSSION

There is little doubt that streamflows in the Deschutes River are uniquely uniform, and that the plan, profile, and pattern of the river are remarkably consistent with time. However, stability does not preclude fluvial processes such as bedload transport and streambed scour-fill. General knowledge of bedload transport as a function of streamflow for spring-fed systems is available. For examples, information is available for Moose Creek, Idaho (Simon, 1999), and for some of the streams being studied by the USFS in the Klamath River, Oregon, water-rights adjudication. These studies generally indicate similarity in bedload-transport behavior between spring-fed and snowmelt rivers.

Water-use facilities upstream of the Pelton-Round Butte dam complex may cause some change in the downstream conveyance of water and sediment. These changes (such as decreased bedload and water discharges) may show up downstream of the Pelton-Round Butte dam complex, but are not a consequence of the complex. The Pelton-Round Butte dam complex is generally operated to cause little attenuation of high flows (those flows capable of bedload transport and thus most related to channel and habitat maintenance). Thus, assessment of the effect(s) of the dam complex should concentrate on sediment-transport characteristics; that is, it should emphasize an upstream-downstream comparison of bedload transport, concurrent scour-fill, and the longer-term degradation-aggradation of the streambed.

Computed bedload-transport rates (Fassnacht, 1998) suggest infrequent occurrence of bedload in the Deschutes River. However, this computed behavior is not consistent with observed behavior in many gravel-bed rivers. Computational techniques included no constraints on the availability and mobility of bed material, equal mobility of particle sizes, and general streamwide mobility — all factors that may not be true for bedload transport in gravel-bed rivers. Input data included some site-specific criteria (like bed-material particle sizes that were extrapolated streamwide from limited determinations) and some empirical factors that are generally characteristic of the several rivers for which the computational scheme was developed.

More recently, Bakke and others (1999) have shown that site-specific calibration of predictive bedload models greatly extends the usefulness and validity of the predictions. Calibration is accomplished with field-measured bedload-transport rates and particle sizes, and with adequate bed-material sampling. Generally, about 20 bedload samples are required. Accordingly, quantification of bedload transport should be based on measured bedload data or determined from predictive models that are locally calibrated with measured bedload data.

The necessity of a bedload-sampling program can easily be tested by assessing streambed mobility using tracer-particle techniques to verify predictions of mobility computed by Fassnacht (1998). If no bed-material mobility is detected, there is little need to proceed with bedload measurements that are more difficult and costly. The most simple tracer-particle technique is painted rocks (references are abundant, but the likely original reference is Leopold and others, 1966). The technique requires taking rocks, usually of known sizes and weights, painting them (perhaps of various colors) and placing them in transects or grids on the streambed. After flows of various but known magnitudes, the placement area is checked for presence and absence of the various sizes of rocks. Additional information of distance moved is gathered if rocks are found and identified (usually by reweighing) and collated to placement location.

An enhanced scheme is to place radio transmitters in rocks (Emmett and others, 1996); different frequency transmitters allow detection of specific rocks, and location after movement is easily determined — even buried locations. Rocks do not have to be recovered to be located, and multiple observations provide detail of the sporadic nature of the movement.

Alternative to surface placement of painted rocks, painted rocks can be placed as shallow columns in cylindrical holes excavated into the streambed. If painted rocks are moved during times of higher streamflow and subsequently covered by unmarked rocks, the amount of scour and subsequent fill can be measured after the original placement location is found. Observations of scour and fill are important in understanding channel and habitat maintenance. Scour and fill is more routinely determined by comparison of repetitive cross sections during the passage of high water (Emmett and Leopold, 1963); the painted rock columns allow detection of scour and fill at locations where repetitive transects are not possible.

Scour chains also allow determination of scour and subsequent fill without the need for cross-section surveys during high flow. The technique is well documented (Emmett, 1965; Leopold and others, 1966). A chain is placed vertically into the streambed; the chain bottom is fixed below maximum scour depth and the chain top is at the streambed surface. After scour, a portion of the chain is left horizontal at the depth of scour. The depth of scour corresponds to the length of horizontal chain, and the depth of fill is the material atop the horizontal chain. After the initial measurement, subsequent measurements may require bookkeeping because the chain top may no longer be at the streambed surface.

Painted-rock and scour-chain techniques are reasonably simple and inexpensive; ideally, such observations on the Deschutes River would include comparisons upstream and downstream of the Pelton-Round Butte complex. Upstream locations would emphasize the Crooked River and Deschutes River arms to Lake Billy Chinook; downstream locations would emphasize sites above and below the confluence with Shitike Creek and its significant contribution of bedload.

Should tracer particles indicate bed mobility more frequent than that computed by Fassnacht (1998), measurement of bedload-transport rates should be undertaken. Because the need for bedload sampling remains undetermined, a sampling program is not detailed in this document. But suffice to mention, an acceptable bedload sampler exists (Helley and Smith, 1971; Emmett, 1980a) and bedload-sampling schemes are established (Emmett, 1980b, 1981, 1984; Edwards and Glysson, 1998). If bedload measurements are made, local calibration of the bedload model used by Fassnacht (1998) could be done and the results compared to results of the uncalibrated model.

Finally, a long-term monitoring program of repetitive surveys at several permanent transects downstream of the Pelton-Round Butte complex would provide factual observation of channel change with time. Some details of such observations have been described (Leopold, 1973; Emmett, 1974; Harrelson and others, 1994). This monitoring program should include observations of bed-material size (see Wolman, 1954) as well as of channel shape.

SUMMARY OF RECOMMENDATIONS

1. Tracer particles to assess frequency of bed mobility for comparison with bed mobility at critical flows suggested from the bedload model:

   - painted rocks, placed along cross-channel transects or in grids on the streambed, or placed as columns in shallow cylindrical holes in the streambed.
   - radio-tagged rocks, generally in size from the 50th to the 84th percentile ($d_{50,}$, d_{84}), placed at representative locations in the cross section.

   These studies would ideally compare behavior just upstream of Lake Billy Chinook (Crooked and Deschutes Rivers) to behavior downstream of the dam complex (above and below the confluence of Shitike Creek with the Deschutes River).

2. Observations of seasonal scour and fill for comparison with the frequency of bed mobility suggested from the modeled flows:

   - columns of painted rocks (see also 1 above).
   - scour chains.

- time-series (especially during the passage of high water) comparison of channel cross section from discharge measurements at the USGS cableway.
- seasonal (high flow to low flow) comparison of channel cross section from level surveys at several sections above and below the confluence of Shitike Creek with the Deschutes River.

3. Observations of long-term aggradation and degradation:
    - annual comparison of channel cross section from level surveys at several sections above and below the confluence of Shitike Creek with the Deschutes River (see also 2 above).
4. Program of bedload sampling:
    - implemented if the bed-mobility assessments (from 1 and 2 above) indicate a need.

Supporting the recommendations for fluvial geomorphology is the proposal for installation of streamflow gages on the three principal inflows to Lake Billy Chinook. Telemetering of real-time hydrologic data could improve the design of an operating policy whereby high streamflows below the dam closely mimic high streamflows that would have occurred in the absence of the dams.

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