AN ABSTRACT OF THE THESIS OF

Ellen M. McClure for the degree of Master of Science in Geology and Civil Engineering presented on January 22, 1998. Title: Spatial and Temporal Trends in Bed Material and Channel Morphology Below a Hydroelectric Dam Complex, Deschutes River, Oregon.

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This study assesses the geomorphic impacts upon the Lower Deschutes River, Oregon below the Pelton Round Butte Hydroelectric Project. A conceptual model of spatial and temporal patterns of bed material size is proposed and considers changes in the frequency of bed-mobilizing flows and sediment supply following river impoundment. The model predicts that on rivers where sediment transport rates are low over the longer term and few bed-mobilizing events have occurred since dam construction, longitudinal patterns of bed material and morphologic adjustments will be limited. Measurements of bed material texture around islands and across submerged bars were taken prior to and following the record February 1996 flood. The results show no trend in surface and subsurface bed material size and armoring ratios with distance downstream from the dam before and after the flood. Tributary inputs of bed
material do not produce abrupt shifts in mainstem grain-size distributions. Historical aerial photographs and cross-sections demonstrate that net morphologic changes since impoundment have been minor. Major flood events in 1964 and 1996 led to planform changes concentrated at the confluence of Shitike Creek and minor fluctuations in bed elevations at cross-sectional sites. Overall, there are no apparent progressive channel adjustments with distance downstream of the Project or with time. Instead, the presence of the macrophyte *Ceratophyllum demersum* influences the grain-size distribution locally by trapping fine sediment. Results from this study suggest that for rivers where there is minor alteration to the flow regime and sediment supply and transport rates are low over longer time scales, measurable geomorphic impacts may be subdued.
Spatial and Temporal Trends in Bed Material and Channel Morphology Below a Hydroelectric Dam Complex, Deschutes River, Oregon

by

Ellen M. McClure

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Ellen M. McClure, Author
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INTRODUCTION

River impoundment influences fluvial processes in downstream alluvial channels in two fundamental ways: it alters the flow regime and intercepts sediment that would otherwise be transported down the channel (Petts 1980). River regulation thus alters the spatial and temporal pattern of sediment transport downstream from the point of regulation, resulting in adjustments of channel processes, morphology, and particle size.

A continuum of possible adjustments exists; actual changes reflect the degree of change in flows and sediment load, the type and quantity of sediment input below the impoundment, and the relative erodibility of bank materials (Petts 1980), as well as the frequency of competent flows. Case studies of geomorphological response to changes in hydrology and sediment supply illustrate a wide variety of textural and morphologic responses in space and time (Petts 1979, Williams and Wolman 1984, Collier et al. 1996).

Typical responses to river impoundment are influenced by tributary inputs of bed material and the frequency of bed-mobilizing flows downstream of a dam (Figure 1). Multiple responses may be observed on the same river, as flow or channel morphology changes with distance from the point of regulation or with time. Most commonly, when flows that mobilize the bed are frequent and sediment supply is low after regulation, selective erosion of finer bed material leads to channel degradation (deepening) and coarsening of surface bed material immediately downstream of the dam (Figure 1d;
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**Frequency of bed-mobilizing flows**

Figure 1. Summary of major downstream geomorphic impacts of river impoundment.
Leopold et al. 1964, Williams and Wolman 1984, Galay et al. 1985). As channel gradient decreases and bed material coarsens with time, the tendency may shift from downcutting to channel widening (Xu 1996). Where tributaries input large volumes of bed material that are transported infrequently post-regulation, aggradation (Church 1995, Collier et al. 1996) and abrupt shifts in the longitudinal pattern of surface bed material size (Church and Kellerhals 1978, Petts 1984b) may be noted (Figure 1a). Mid-channel bars and islands may form near tributary confluences. Bank erosion in this setting may also lead to the construction of islands and bars by expanding channel widths and decreasing flow velocities while large volumes of sediment are introduced to the channel (Xu 1997).

Where tributary inputs of bed material are high and bed-mobilizing flows are frequent after regulation, only weak armoring should be present (Figure 1b). Textural shifts near tributary confluences may also occur, depending on the contrast between mainstem and tributary grain-sizes. When sediment supply is low and the bed moves infrequently, channel responses, if any, may be more subtle and primarily involve changes in the size distribution of the bed material (Figure 1c). In all cases, responses are likely to include some textural adjustments of the bed material.

The total length of affected reaches may extend many kilometers downstream and be separated by zones showing no evidence of change (Petts 1980). On most rivers, channel responses are focused in the first few kilometers or tens of kilometers below the dam (Williams and Wolman 1984), although some authors report progressing fronts of changes extending as far as 250 km (Collier et al. 1996). As sediment inputs from tributaries and banks increase, or as the river adjusts other parameters, geomorphic impacts may become undetectable at some distance downstream.
In this study, we examine the spatial and temporal responses to channel impoundment on the Lower Deschutes River, Oregon. Since 1957, the Lower Deschutes River has been regulated at the Pelton Round Butte Hydroelectric Project, owned and operated by Portland General Electric (PGE). The original 50-year license for the dams expires in 2001, so PGE is currently applying for relicensing through the Federal Energy Regulatory Commission. In the meantime, PGE is having independent scientists assess any impacts the dams may be causing and explore the conditions under which the Project should operate in the future. This study addresses downstream geomorphic impacts, such as changes in bed material properties and channel morphology. Extensive measurements of surface and subsurface bed material were used to identify textural patterns with downstream distance from the Project and following the February 1996 flood. Historical photographs and cross-sections were studied for spatial and temporal patterns in morphologic adjustment. A conceptual model for downstream textural responses is used as a framework for interpreting these results.

Several studies have examined the effects of dams on gravel recruitment and quality in the Deschutes River (Aney et al. 1967, Huntington 1985). However, these studies have focused on gravel quality as it relates to the character and distribution of fish habitat. This study focuses on bed-material changes below a dam complex within a geomorphic context. Results from this study provide insight on how changes in hydrology and sediment supply can be used to infer geomorphic and, thus, environmental impacts.

During the last few decades, there has been growing awareness of the downstream geomorphic and environmental impacts of river impoundment. Most recently, this has
led to efforts to mitigate those deleterious impacts, as exemplified by the March 1996 experimental flood release from the Glen Canyon Dam on the Colorado River. The habitats of fish and benthic organisms are intimately associated with the hydrological, sedimentological, and morphological characters of river channels. Negative physical changes impact, in turn, the biologic integrity and aesthetic and recreational potential of rivers. As our understanding of channel responses to impoundment improves, we can better predict geomorphic changes in a variety of environmental settings and reduce negative impacts.
CONCEPTUAL MODEL

On regulated rivers, successive grain-size measurements generally are not available for pre-dam time periods or for successive time periods following dam closure. In the absence of a pre- and post-dam comparison of grain-size changes, a single "snapshot" of downstream longitudinal trends in the size of the surface and subsurface bed material can be used to evaluate the extent and magnitude of channel response. As finer particles are selectively eroded from the stream bed and not replaced by bed material from upstream, coarsening of the surface armor layer may occur. Thus, high armoring ratios ($D_{50 \text{ surface}}/D_{50 \text{ subsurface}}$, where $D_{50}$ represents the grain-size diameter for which 50% of the material is finer) close to the dam may result from bed surface coarsening in response to decreases in sediment supply (Dietrich et al. 1989). Further downstream surface grain-sizes and armoring may decrease as the channel bed approaches quasi-equilibrium between increasing flows and sediment yields from tributaries and constraints imposed by the historic channel morphology and composition of the bed. Far from the point of regulation, longitudinal patterns in bed material properties due to the dam may be dampened, locally overprinted, or no longer distinguishable.

We hypothesize that the pattern of surface and subsurface bed material size in a reach below a dam will reflect the degree of flow regulation and alteration of the sediment load. To the extent that it is possible for a dam not to influence the downstream flow regime and sediment supply, then there will be correspondingly small changes in bed material texture.
Researchers often use the subsurface grain-size distribution as a proxy for the grain-size distribution of the bedload, since it represents the supply of bed material readily available for transport (Parker et al. 1982). The surface armor layer is thought to reflect the grain-size distribution resulting from winnowing processes or equal mobility of available bed materials under the dominant sediment transport regime. Together, surface grain-sizes, subsurface grain-sizes, and armoring can also be examined to understand channel processes and inputs of sediment.

There is a continuum of textural responses between the four end-members illustrated in Figure 2. Consider the frequency of flow ($F_a$) required to move some index value, (i.e., $D_{50}$) of the surface or subsurface grain-size distribution after impoundment, while $F_b$ represents that same frequency before impoundment. The ratio $F_a/F_b$ can be used to indicate the relative change in frequency of bed mobilizing flows. As $F_a/F_b$ approaches one, flows more closely mimic pre-dam conditions. It is conceivable that $F_a$ could exceed $F_b$, but this is not common (although see Kellerhals et al. 1979 and Church 1995). Where $Q_{sb}$ and $Q_{sa}$ represent the sediment supply prior to and following dam emplacement, respectively, an increase in the ratio $Q_{sa}/Q_{sb}$ to unity represents bedload supply to downstream reaches at pre-dam conditions.

In the case of both ratios approximating unity, there should be no longitudinal trend in the size of surface or subsurface bed material or degree of armoring with downstream distance at the defined reach scale (Figure 2b). This case represents the hypothetical result of a dam with little or no flow modification and no change in sediment supply. This could occur where flows are modified below the threshold required for sediment transport, where sediment transport rates are generally low, and where the input
Figure 2. Conceptual model of longitudinal patterns of surface and subsurface grain-size (here $D_{50}$) with distance from an impoundment. Within each box, the upper dashed lines indicate pre-dam surface grain-sizes. Upper solid lines and curves represent possible post-dam surface patterns. Lower dashed lines indicate pre-dam subsurface grain-sizes. Lower solid lines represent possible post-dam subsurface patterns. Armoring ratios are represented by the ratio of surface and subsurface values.
of material from tributaries and hillslope processes quickly replenishes the intercepted load.

If the sediment supply remains relatively unchanged, but $F_{d}/F_{b}$ approaches zero, then the bed near the dam may undergo surface fining (Figure 2a), aggradation of the riverbed, and/or limited armor development near the dam. This case would apply if tributaries and the bed and bank zones collectively supply more sediment than regulated flows are able to entrain.

For regulated rivers where $F_{d}/F_{b}$ remains largely unchanged but $Q_{sa}/Q_{sb}$ approaches zero, the bed is likely to degrade and coarsen downstream of the impoundment (Figure 2d). The surface bed material becomes progressively coarser with time and proximity to the dam, since entrained sediment is no longer replaced by material transported from upstream. The size of subsurface bed material also increases in response to the decline in supply of sediment. This occurs when post-regulation flows are still competent to mobilize a large fraction of the bed material during high flow events, leaving a lag of coarser particles in both the surface and subsurface layers.

Finally, as both ratios are reduced, any of the aforementioned patterns may result (Figure 2c). The prevailing patterns of surface and subsurface grain-size will reflect which of the two effects predominates.

Changes in subsurface bed material with downstream distance from an impoundment should thus reflect changes in the amount of bed material supplied, while spatial trends in surface bed material should be reflective of joint changes in sediment supply and transport. Finally, the degree of armoring relates changes in both surface and subsurface bed material by site. Differences between the surface and subsurface grain-
size distributions can also be used to identify the fraction of the bedload transported under conditions during which larger armor material is not mobile.

This conceptual model is tested on the Lower Deschutes River, Oregon. We hypothesize that historically low sediment transport rates associated with highly uniform flows due to the river's geological setting may have limited textural adjustments. If this is the case, no longitudinal trends in surface grain-size, subsurface grain-size, or armoring ratios may be apparent (as in Figure 2b). Furthermore, larger scale morphologic adjustments may be minimal. Measurements of surface and subsurface bed material size are used in conjunction with historical cross-sections and aerial photographs to test this hypothesis within the conceptual framework.
STUDY SITE

General Description

The Deschutes River in north-central Oregon flows 329 km east and north from Little Lava Lake to drain about 27,200 km² at its mouth on the Columbia River (Figure 3). Among the Oregon basins, the Deschutes is second in size only to the Willamette River. From 1958 to 1964, a series of three hydroelectric dams was constructed by Portland General Electric Company in the Lower Deschutes River. These constituted the Pelton Round Butte Hydroelectric Project and included the Round Butte Dam (River Kilometer [RK hereafter] 177.7), Pelton Dam (RK 165.6), and the Reregulating Dam (RK 161.1). Other dams were constructed in the upper basin as early as the 1940s.

Downstream of the Project, the Lower Deschutes river is free-flowing and winds through a narrow canyon up to 610 m deep with an average stream gradient of 0.23%. From RK 161.1 to RK 115.9, the river incises Oligocene and Miocene John Day Formation rhyolites and rhyolitic tuffs (Figure 4; Waters 1968a, Waters 1968b). The major geologic unit from RK 115.9 to RK 99.8 is the Eocene Clarno Formation, chiefly zeolitized and partly argillitized andesites and mudflows. Below RK 99.8 the Deschutes cuts down into Columbia River Basalts (Waters 1968a). Large local increases in stream gradient are associated with a large landslide deposit at RK 122.8, a large bedrock knickpoint (Sherars Falls) at RK 70.6, and relic debris flow deposits at RK 19.5 (Harris Island). Otherwise, the gradient of the Deschutes is relatively similar throughout its length (Figure 4).
Figure 3. Location map of the Lower Deschutes River basin. Sample sites on lowermost section indicated by arrows. USGS gaging station sites shown by triangles.
Figure 4. Gradient and major geologic units of the Lower Deschutes River. Vertical lines separate distinct geologic units (based on Waters 1968a, 1968b). Features associated with peaks in gradient are indicated by italics.
The Lower Deschutes River has little floodplain development. The absence of many bars or a continuous floodplain suggests limited sediment storage and transport. Islands are key morphologic and ecologic features, commonly situated in relatively wide reaches of the channel (Figure 5). For the purposes of this study, islands are defined as vegetated mid-channel or marginal sites with surfaces above the average water surface elevation. Several large islands are probably associated with large-scale debris flow and landslide events that occurred in the past. Mid-channel and marginal bars are scarcer features and are submerged, unvegetated, and generally lobate in form. Bed material in the Lower Deschutes River consists mostly of basalt gravel and cobbles with little sand. Patches of sand are associated with marginal deposits, typically in relatively wide sections of the river.

Indigenous vegetation in the lower elevation canyon includes bunch grass, sagebrush, juniper, and ponderosa pine. Riparian vegetation includes perennial grasses, willow, and alder. Although several macrophytes populate portions of the Lower Deschutes, *Ceratophyllum demersum* is by far the most abundant and is concentrated in the reach just downstream of the hydrocomplex. This floating macrophyte occupies zones of shallow, slow-moving waters (Haslam 1987) and is anchored by shoots penetrating bed material. Because of its whorled structure and long branches, the macrophyte can adjust to fluctuating water levels and some turbidity (Davis and Brinson 1980).

There are only four perennial tributaries along the lower 161 river kilometers: Shitike Creek, Trout Creek, Warm Springs River, and the White River. The paucity of perennial tributaries suggests that tributaries may have only a minor effect in the delivery
Figure 5. Photographs of the islands at RK 142.1 (top) and 152.9 (bottom). Views are from river right side looking downstream.
of water and sediment to the mainstem Deschutes. Smaller intermittent streams cut through side canyons along the entire lower river. Small fans at intermittent tributary junctions alter stream width locally.

A reach extending 22 km downstream from the hydrocomplex was selected for study, wherein any textual and morphologic changes due to the dams should be most pronounced (Figure 3). We refer to this as the Primary Study Reach. Shitike Creek, joins the Deschutes in this section. Another smaller tributary, Trout Creek, joins the Deschutes at the downstream end of the reach. Below this, a longer reach was studied to provide comparison and contrast with the Primary Study Reach (Figure 3). The Warm Springs and White rivers join the Deschutes in this lower section.

**Hydrological Setting**

Because the headwaters drain highly permeable Pliocene and Pleistocene basalts (Manga 1996) and the drainage network is geologically young, Lower Deschutes River discharges are strongly dominated by groundwater. As a result, the Deschutes River has the most uniform discharge of any river in the country of comparable size or larger (Henshaw et al. 1914) and seasonal variations in streamflow of a single order of magnitude have been rare (Huntington 1985).

Discharge measurements made at the U.S. Geological Survey (USGS) gaging station 14092500 (RK 159.9, see Figure 3) near Madras, Oregon date back to 1925 and allow for pre-regulation flow analysis for the water years 1925 to 1955. A post-regulation
comparison is based on the water years 1965 to 1995. This omits the period when the
reservoirs were being constructed.

Flow duration and flood frequency curves constructed separately for the pre- and
post-hydrocomplex time periods illustrate the extraordinary uniformity of river flows. On
average, mean annual high flows are twice the size of low flows (Figure 6a). Since 1964
the difference between the 1 and 99% exceedance probability is only a factor of 4.

The curves also show that hydrologic conditions in the basin have undergone
relatively little change following impoundment. In general, all mean daily flows have
been higher during the post-hydrocomplex time period (Figure 6a), but the difference is
only 3.5% for the 50% flows. High flow events are slightly higher during the post-dam
time period (Figure 6b). Ten-year flood events are estimated to be about 16% larger
following impoundment. All of these differences may be due to climatic variability
and/or basin development. They do not necessarily show any effects of the Pelton Round
Butte Hydroelectric Project.

There have been two particularly large floods during the period of gaging on the
Lower Deschutes: the December 1964 and February 1996 floods. The maximum
recorded discharge at Madras, 546 cms instantaneous peak (mean daily flow of 510 cms),
occurred on February 8, 1996. Flood frequency curves predict this was approximately a
100-year event based on the period of record. The February 1996 flood resulted from an
unusually wet winter, causing saturated soils in the Deschutes Basin and high reservoir
levels. The subsequent combination of record rainfalls and warm temperatures led to
rapid melting of a deep snowpack and severe flooding. Flooding in the upper basin was
considerably less pronounced than on the Lower Deschutes River. Shitike Creek peaked
Figure 6. Flow duration and flood frequency curves for USGS gaging station in the Primary Study Reach. Magnitude of February 1996 flood shown for comparison.
at 92 cms on February 6. Large western tributaries draining the Cascades, such as the Warm Springs and White Rivers, greatly augmented mainstem flows. At the USGS gage 14103000 at Moody (RK 2.3, see Figure 3), flow in the Deschutes reached 1989 cms.

The December 1964 flood is the second largest of the record (mean daily flow of 428 cms at Madras gage) and also resulted from a rain-on-snow event. The hydrocomplex was first filled during this event. Other post-dam peak mean daily flows were recorded near Madras in February 1982 (405 cms), February 1958 (360 cms), January 1965 (348 cms), and March 1972 (343 cms).
METHODS

Field Sampling

Field sampling was stratified geomorphically at two levels. First, islands and bars were selected for sampling bed material, since they represent the dominant depositional forms in the river and allow comparisons between sedimentologically similar sites (Kondolf 1997). Individual sample sites were selected based on intensive field reconnaissance and aerial photographs. Sample sites included islands and bars of comparable hydraulic settings along which sampling grids could be safely established under the observed flow conditions.

Around each island four distinctive geomorphic “environments” were sampled: the head (upstream end), the side (side abutting main flow), the side channel (side bordering secondary channel), and the end (downstream end) (Figure 7). Flow tended to be deepest and fastest at the head and side of an island. At the end of an island, flow velocities were generally lowest and patches of sand were common. The head and end environments of selected bars were also sampled.

The sampling design allowed for the analysis of grain-size variability at three distinct spatial scales: 1) within a sample plot, 2) between sample plots around an individual island or bar, 3) and between different islands and bars. The conceptual model proposed in this study focuses on detecting patterns at this largest spatial scale. Grain-size patterns at the two smaller spatial scales also are analyzed to describe variability owing to local hydraulic differences (depths, velocities, and shear stresses), since other
Figure 7. Schematic of sampling design at vegetated island and submerged bar. The location of head, side, side channel, and end environments are shown as smaller rectangles. Squares represent grids for pebble counts of surface bed material. Circles indicate positions of subsurface samples.
factors (sediment supply and distance from the hydrocomplex) are relatively constant at these scales. If longitudinal patterns exceed smaller scale variability in grain-size, this would provide evidence of a textural impact of the Pelton Round Butte Hydroelectric Project.

In the summer of 1995, the environments of 12 islands and bars were sampled in the Primary Study Reach immediately downstream of the hydrocomplex (Figure 8). To document changes following the February 1996 flood of record, the heads of these sites were resampled during the summer of 1996. Eleven island heads in the lowermost 140 km of the river were also sampled during the summer of 1996 to extend the analysis downstream to the Columbia River (Figure 3). These sites were selected using the same criteria applied to the Primary Study Reach. Following the February 1996 flood, at each of these sites in the upper and lower reaches, the amount of disturbance to the island perimeter, surface, and vegetation was noted.

In general, surface bed material was sampled within each environment using three standard pebble counts of 100 particles (Wolman 1954). Three overlapping 10 m by 10 m grids were established across the bed. The intermediate b-axis of each grain immediately beneath a grid point was measured in millimeters. Smaller particles were binned into a <2 mm category in the field. All particles were sampled by one operator; this eliminated any possible user-dependent bias (Hey and Thorne 1983, Marcus et al. 1995). Grids were aligned in trios with two grids having one common side and the third grid straddling half of each of the former (Figure 7). The middle grid was displaced 50 cm downstream of the center point to avoid choosing previously sampled particles. The sampling area was therefore a 20 by 10 m grid with the long axis approximately parallel
Figure 8. Location map of sample sites in the Primary Study Reach. USGS gaging station shown by triangle. USGS cross-section site shown by asterisk.
to the island and flow direction (Figure 7). Sample grids on island heads and ends were centered along the flow-parallel axis of the island and spaced no more than 3 meters from the vegetated island perimeter. The upstream end of grids along the side and side channel of islands was situated about one-third of the flow-parallel length of the island from the island head (Figure 7). Sample grids on bars were centered on the longitudinal axis of the bar at both the head and end. The imposition of a grid system insured measurement independence. In addition, the use of grids permitted the testing of autocorrelation within each trio of grids. At each point where a particle was sampled, the presence of the macrophyte C. demersum was also noted. Since the plant can trap fine sediment on the bed surface, it was necessary to account for its abundance in the later analyses.

Due to logistical reasons, not all of the four environments or all three grids in each environment could be sampled in 1995 (Table 1). Island heads were selected for the most detailed analysis, and they were sampled at all sites in both years. There were four island heads in 1995 for which only two grids were sampled (Table 1). For 5 island heads in 1995, the entire pebble count trio was resampled, such that overall 600 particles were measured. For remaining sites in 1995 and all island heads in 1996, three 100-particle pebble counts were conducted. Although Wolman (1954) suggested that 100 particles was sufficient for sampling, Rice and Church (1996) recommend 400-stone samples to improve estimates of all percentiles to within a tenth of a phi unit within 95% confidence limits. In this study, the clustering of pebble counts in an area allowed for the pooling of the particles to form individual pebble counts of 200 to 600 particles for each site. This effectively reduced the sample number to 1 for each island head. Although this restricted the total number of sampled island heads in both years to 23, statistical methods used
Table 1. Summary of sample size of surface and subsurface bed material by year and environment.

<table>
<thead>
<tr>
<th>River kilometer of site</th>
<th>Number of 100-particle pebble counts conducted</th>
<th>Volume of subsurface bed material retained (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Head</td>
<td>Head Side</td>
</tr>
<tr>
<td>PRIMARY STUDY REACH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160.7</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>160.3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>159.3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>158.0</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>155.8</td>
<td>3</td>
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</tr>
<tr>
<td>152.9</td>
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</tr>
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</tr>
<tr>
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</tr>
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<td>3</td>
</tr>
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</tr>
<tr>
<td>144.3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>142.1</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

ENTIRE LOWER RIVER

|-------------------------|        |          |        |          |        |          |
| 138.9                   | 3      | n/a      | n/a    | n/a      | 25.0   | n/a      |
| 133.5                   | 3      | n/a      | n/a    | n/a      | 26.4   | n/a      |
| 123.9                   | 3      | n/a      | n/a    | n/a      | 20.6   | n/a      |
| 114.1                   | 3      | n/a      | n/a    | n/a      | 23.4   | n/a      |
| 97.4                    | 3      | n/a      | n/a    | n/a      | 18.2   | n/a      |
| 83.6                    | 3      | n/a      | n/a    | n/a      | 27.8   | n/a      |
| 64.5                    | 3      | n/a      | n/a    | n/a      | 21.6   | n/a      |
| 51.2                    | 3      | n/a      | n/a    | n/a      | 21.0   | n/a      |
| 42.3                    | 3      | n/a      | n/a    | n/a      | 22.7   | n/a      |
| 38.6                    | 3      | n/a      | n/a    | n/a      | 24.8   | n/a      |
| 15.2                    | 3      | n/a      | n/a    | n/a      | 27.4   | n/a      |

NOTE: n/a = not applicable, --- = not sampled
degrees of freedom to estimate variability between island heads longitudinally, rather than variability between pebble counts at each island head. Statistical methods, therefore, more accurately detected any longitudinal patterns in grain-size at the reach scale. The comparison of individual pebble counts conducted at an island head could, however, be used to estimate grain-size variability within a grid trio and precision with increasing sample size.

At each main channel site where surface sampling was conducted, particles below the surface armor layer were also sampled. For both years, individual samples averaged about 20.3 kg by dry weight. To prevent the washing of fines downstream, a sawed off 55-gallon barrel cylinder was worked vertically into the submerged bed. The armor layer, identified as the surface layer extending to the depth of the largest particle in the surface layer, was removed by hand and subsurface material extending to a depth between one to two times the thickness of the armor layer was scooped into a bucket. Water collected in the scoop was also added to the bucket to retain finer particles put into suspension. At least one subsurface sample was collected beneath each pebble count grid in summer 1995. Thus, for sites where a trio of grids was established, three subsurface samples were retained (Figure 7). To expedite sampling in the summer of 1996, only a sample from the middle grid was obtained. All samples were dried in the laboratory and sieved using a progression of U.S. Standard sieves: 4 in., 3 in., 2 in., 1.5 in., 1 in., 0.75 in., 0.5 in., 0.375 in., 0.25 in., #4, #8, #16, #30, #50, #100, #200, #230, and pan (thus spanning the range from 101.6 mm to <0.063 mm).

Bulk samples taken in 1995 were pooled to form samples averaging 60.9 kg for each site (Table 1). Church et al. (1987) recommend that the largest clast comprise no
more than 0.1% of the sample size by weight (this can be relaxed to 1% for coarse sediments) for an adequate bulk sample. Since a large cobble sometimes comprised more than 1% of a sample by weight, this is smaller than could guarantee good precision, particularly for the smaller samples taken in 1996. Some particles in 1996 samples were as much as 18% of the sample by weight. However, ideal sample sizes in such coarse sediments are difficult to obtain and were beyond the resources of this study. Although the upper percentiles of the samples could have been truncated so that the lower grain-size distribution would have been representative and comparable between sites (Church et al. 1987), this would have made it impossible to compare the full grain-size distribution. It was hoped that this would still roughly characterize subsurface grain-size distributions, although some bias could be present.

Pebble counts of 400 particles were also conducted along reaches of 2 to 10 channel lengths on major tributaries by pacing back and forth between the bankfull channel margins. These were conducted within Shitike Creek in the Primary Study Reach and 13 tributaries farther downstream. For each site, sampling was conducted near the confluence with the Lower Deschutes but above the zone where backwater effects are likely during high flow events. Grain-size measurements from tributaries were used to identify local sources of sediment that could interrupt textural patterns within the mainstem.
Longitudinal Analysis

For surface and subsurface samples, percentiles of the grain-size distribution ($D_5$, $D_{10}$, $D_{25}$, $D_{50}$, $D_{75}$, $D_{84}$, $D_{95}$) were computed by site on the phi scale and then backtransformed to millimeters. From these values the armoring ratio was calculated for each site as $D_{50 \text{ surface}}$ (mm)/$D_{50 \text{ subsurface}}$ (mm). Trask's sorting coefficient was computed as ($D_{75}$ (mm)/$D_{25}$ (mm))$^{1/2}$ (Krumbein and Pettijohn 1938), such that higher values indicate poorer sorting.

Because grain-size percentiles in one grain-size distribution are inherently interdependent, only $D_{50}$ values underwent statistical testing. The surface, subsurface, and armoring data were analyzed separately using multiple linear regression with STATGRAPHICS Version 7.0 (Statistical Graphics Corporation 1993). Each model for surface grain-size, subsurface grain-size, and armoring included variables for river kilometer and year. Since these two variables were designed to identify spatial and temporal patterns rather than to build a predictive model, they were not dropped from the model even if they were not statistically significant. Models for surface grain-size also included a variable for the abundance of *C. demersum*; however, this variable was dropped from a model if it was not significant. Models, therefore, tested for any longitudinal trend in grain-size and for changes following the 1996 flood, while accounting for the abundance of *C. demersum* at each site.

Statistical analyses were conducted separately using data from the Primary Study Reach (1995 & 1996) or the entire lower river (1996 only). Indicator variables were assigned to represent the 1995 and 1996 years. The abundance of *C. demersum* was
expressed categorically with low (0%), moderate (1-20%), and high percentages (>20%) of particles associated with the macrophyte. Interactions between variables were tested at the 0.05 significance level and dropped for higher values for each pebble count trio from a sample site.

Following these guidelines, the following final models were developed:

**Primary Study Reach**

\[
\left| \mu(\text{surface } D_{50}) \right| = \beta_0 + \beta_1(\text{RKM}) + \beta_2(\text{YEAR}) + \beta_3(\text{CD}) + \beta_4(\text{CD}) \\
\left| \mu(\text{subsurface } D_{50}) \right| = \beta_0 + \beta_1(\text{RKM}) + \beta_2(\text{YEAR}) \\
\left| \mu(\text{armor}) \right| = \beta_0 + \beta_1(\text{RKM}) + \beta_2(\text{YEAR})
\]

**Entire Lower Deschutes**

\[
\left| \mu(\text{surface } D_{50}) \right| = \beta_0 + \beta_1(\text{RKM}) \\
\left| \mu(\text{subsurface } D_{50}) \right| = \beta_0 + \beta_1(\text{RKM}) \\
\left| \mu(\text{armor}) \right| = \beta_0 + \beta_1(\text{RKM})
\]

where \( \mu \) = the estimated mean, RKM = river kilometer, YEAR = year, CD = the level of *C. demersum*, and \( \beta \) values represent coefficients in each regression model (\( \beta_2 = 1 \) for 1996, \( \beta_3 = 1 \) for moderate levels of *C. demersum*, \( \beta_4 = 1 \) for high levels of *C. demersum*).

For each final model, the effect of influential points was evaluated. Significance of variables in the final models was assessed at the 0.05 significance level. Since any autocorrelation found within sample plots would be at a scale smaller than the final
sampling unit ($D_{50}$ of island or bar head), the inclusion of $D_{50}$ values from sites
demonstrating within-plot autocorrelation did not violate the assumption of sample
independence. No autocorrelation between $D_{50}$ values from the heads of islands and bars
was identified.

The small number of data points ($n=24$ for regressions of Primary Study Reach,
$n=23$ for regressions of entire lower river) increases the potential for individual points to
exert strong influence on a regression. But by exploring the role of each statistically
influential point while preserving each in the final models, the analyses offer a
conservative reporting of spatial and temporal grain-size characteristics.

**Planform and Cross-Section Analysis**

Black and white aerial photographs from 1944 (approximate scale 1:22,400), 1951
(scale 1:20,000), 1956 (scale 1:20,000), 1968 (scale 1:20,000), and 1972 (scale 1:20,000),
were examined with infrared photographs from 1995 (scale 1:2,000) and video stills
(scale varies, ~1:2,000) to evaluate planform changes with time. Detailed analysis was
focused on the Primary Study Reach, where photographic coverage was best. Particular
attention was paid to changes associated with major flood events and at tributary
junctions.

Cross-sectional measurements first made in 1958 at RK 160.4 (just 0.7 km below
the Reregulating Dam) and made since 1931 at RK 2.3 were also analyzed for elevational
changes of the bed. At both sites, the channel is relatively straight. There is a submerged
midchannel bar at the site at RK 2.3.
For cross-sections at RK 160.4, a common, upper arbitrary datum was chosen near the top of the cross-sections as a basis for comparison. Using WinXSPRO (USDA Forest Service 1996), maximum depth, area, width, and perimeter were calculated for below this elevation.

**Within-Plot Spatial Analysis**

Measurements of surface bed material were checked for small-scale patterns that could illustrate grain-size variability attributable to small-scale processes. For example, flow decelerating downstream of larger surface particles could lead to the deposition of sand. Thus, patterns of grain-size within individual sample plots could result from localized hydraulics and inter-particle effects.

To identify any spatial dependence between surface particles, correlograms and semivariograms were constructed for 1996 sample plots at island heads within the Primary Study Reach. The theory and application of these techniques has been well documented in ecological literature (Legendre and Fortin 1989, Rossi et al. 1992). A semivariogram is a plot of sample variance versus lag distance (the distance between paired sample points). Semivariograms were examined for evidence of spatial dependence between surface particle sizes and for any spatial gradient (a gradual, continuous change across a data set in space). A correlogram relates a spatial autocorrelation coefficient, such as Moran’s I, to lag distances and tests the null hypothesis that there is no spatial dependence between data points. Correlograms were used to describe the patchiness bed material. Statistically significant (p<0.05) positive
values of Moran’s I indicate the lag distance between similarly sized particles or patches of particles. Significant negative values of Moran’s I indicate the lag distance between particles of very different size.

Particles binned as less than 2 mm were assigned a value of 1 mm for the purposes of conducting further computations. Particle size measurements in millimeters were converted to the phi scale (-log₂ [mm]) to normalize each grain-size distribution. Percentile data were tested for normality and equality of variance.

Separate correlograms and semivariograms were plotted for each island or bar head using a statistical program written in C language and based on Legendre and Fortin (1989). It was possible to compute valid coefficients even in the right-hand portion of the correlogram, because distance classes were formed with classes of equal frequencies (Legendre and Fortin 1989). Since correlation coefficients are likely to overestimate autocorrelation for sites with many paired null values (phi value corresponding to particles assigned 1 mm diameter), this technique is more likely to overestimate than not detect autocorrelation (Legendre and Fortin 1989). Anisotropy (a pattern in a spatial data set which violates the assumption of a constant mean in all directions) was assessed using uni-dimensional correlograms and variograms in S-PLUS Version 3.4 (Mathsoft, Inc. 1996).
RESULTS

**Bed Material Analysis**

Grain-size data are analyzed at three distinct spatial scales. First, textural properties of the separate hydraulic environments around bars and islands are described for all sites in the Primary Study Reach. Results from this scale illustrate textural contrasts owing to hydraulic differences at a site.

Second, larger-scale patterns of grain-size are characterized with respect to distance from the hydrocomplex, as well as between years. Spatial and temporal patterns of surface grain-size, subsurface grain-size, and armoring are considered separately. The effect of tributary inputs of sediment on longitudinal patterns of surface grain-size is also considered. Finally, spatial patterns within individual 10-m by 20-m sample plots are described.

**Between-Environments Analysis**

Grain-size distributions vary characteristically with depositional environment at individual islands and bars sampled in 1995. In the Primary Study Reach, island side and head environments generally have the coarsest surfaces, with $D_{50}$ values averaging about 81 and 71 mm, respectively. Surface $D_{50}$ values from side channels are considerably finer (average $D_{50}$ of 56 mm). The finest surface grain-sizes are located at the ends of islands and bars, where surface $D_{50}$ values average 46 mm. Such a pattern is typified by the island at RK 147.7 (Figure 9). Median surface grain-sizes from side and head
Figure 9. Surface and subsurface grain-size distributions from the four environments around the island at RK 147.7. Trask sorting coefficients and armoring ratios also shown. Side and head environments have coarsest surface and subsurface bed material.
environments of all 1995 sample sites show less variation than do side channel and end environments, where standard deviations of $D_{50}$ between sites reach about one half of average $D_{50}$ values. Average Trask sorting coefficients for the head, side, side channel, and end environments (2, 1.5, 2.2, and 3.9; respectively) suggest that the ends of islands exhibit the poorest sorting.

Subsurface grain-sizes around islands and bars in the Primary Study Reach are consistently finer and more poorly sorted than surface grain-sizes. As with surface grain-sizes, subsurface grain-size distributions from head and side environments tend to be markedly coarser (average $D_{50}$ of 25 mm for each) than side channel and end environments (average $D_{50}$ of 17 and 20 mm, respectively). Average sorting at head, side, side channel, and end environments (3.6, 3.7, 3.6, and 4.5, respectively) demonstrate that grain-size distributions at the ends of islands and bars are the most poorly sorted.

The degree of armoring is generally similar among the head, side, and side channel environments (average ratio of 3.1, 3.4, and 3.2, respectively), while end environments tend to be least armored (average ratio of 2.4).

Further grain-size analyses were based exclusively on island and bar head environments. This reduced the between-site variability of grain-size and armoring due to local hydraulic differences rather than longitudinal patterns with distance from the hydrocomplex. Field investigations suggested that, of the four sampled environments, bed material at island heads (and sides) better approximates that of the larger cross-section at any sample site. In addition, since the head environment is present for both islands and bars, all sample sites could be utilized in the longitudinal analysis.
Longitudinal Analysis

Results from multiple regression analyses were variable but largely showed no longitudinal or temporal trends. The coefficients and associated two-sided p-values for each model are displayed in Table 2.

Primary Study Reach: Surface Grain-Size

In the Primary Study Reach, surface $D_{50}$ values at island and bar heads during both years ranged from 31 mm to 93 mm (Figure 10) and average 69 mm. There is little or no apparent longitudinal trend in surface $D_{50}$ (Figure 10). Results from multiple linear regression show no evidence for a change in surface $D_{50}$ with distance, even after accounting for the year and abundance of *C. demersum* (Table 2). One influential point was identified in the regression. When this point was removed from the final model for comparison, the results remained unchanged.

In addition, Trask's sorting coefficient shows very little difference in surface particle sorting between sites (Figure 11). The coefficient generally ranged between 1.3 and 2.7, but reached 5.9 at the island at RK 142.1 in 1995. Thus, greater sorting within surface deposits was not observed close to the hydrocomplex.

Spatial variations in grain-size between sites are strongly influenced by the abundance of *C. demersum*, but not by distance from the hydrocomplex. The four lowest $D_{50}$ values represent two sites (islands at RK 142.1 and RK 159.3, Figure 10) where macrophyte levels were especially high for both years. There was strong statistical evidence that $D_{50}$ was associated with the amount of *C. demersum* (p-value = 0.006; extra
Figure 10. Surface $D_{50}$ values for island heads in the Primary Study Reach.
Table 2. Summary of regression results for the Primary Study Reach and lower river. Asterisks indicate statistically significant (<0.05) p-values.

| Independent variables | Surface $D_{50}$ (mm) | | Subsurface $D_{50}$ (mm) | | Armoring ratio (mm/mm) | |
|-----------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
|                       | Value of β Coefficient | 2-sided p-value | Value of β Coefficient | 2-sided p-value | Value of β Coefficient | 2-sided p-value |
| **PRIMARY STUDY REACH** |                       |                       |                       |                       |                       |                       |
| Constant (Low C. dem., 1995) | -34.30 | 0.68 | 110.74 | 0.044* | -21.00 | 0.062 |
| RKM                   | 0.73 | 0.19 | -0.56 | 0.11 | 0.16 | 0.034* |
| YEAR (0 for 1995, 1 for 1996) | 6.53 | 0.32 | -6.54 | 0.14 | 1.68 | 0.07 |
| C. demersum: (1 for moderate) | 1.54 | 0.84 | n/a | n/a | n/a | n/a |
| C. demersum: (1 for high) | -28.12 | 0.0052* | n/a | n/a | n/a | n/a |
| **ENTIRE LOWER RIVER** |                       |                       |                       |                       |                       |                       |
| Constant | 87.68 | <0.0001* | 30.14 | 0.0003* | 2.59 | 0.07 |
| RKM | -0.13 | 0.23 | -0.08 | 0.14 | 0.02 | 0.14 |

n/a = not applicable
Figure 11. Trask sorting coefficients for surface bed material at island heads in the Primary Study Reach. Higher coefficients indicate poorer sorting. Large square represents value of sorting coefficient for Shitike Creek at its confluence.
sum of squares F-test) in this reach. In particular, high levels of *C. demersum* are strongly significant in lowering the median grain-size (Table 2).

There is also little change in surface $D_{90}$ between years at each site (Figure 10). Even after accounting for the effects of *C. demersum*, there is also no statistical evidence for a change in surface $D_{50}$ following the 1996 flood (Table 2). Although the grain-size distribution at most sites underwent little change, at several sites there are some temporal shifts in surface grain-size not fully apparent in the analysis of $D_{50}$ (Figure 12). At the island at RK 147.7, nearly the entire grain-size distribution fined after the 1996 flood, yet no obvious sources of finer bed material are apparent immediately upstream of this section. Local hydraulics associated with this widened section may have led to the deposition of finer particles. Although $D_{50}$ changed little between the two years at the island at RK 155.8, surface bed material become more poorly sorted (Figure 11). The proximity of this site to Shitike Creek suggests that tributary inputs of bed material during the February 1996 flood may have altered local grain-size distributions in the mainstem Deschutes.

At a few sites, temporal changes in the surface grain-size distribution corresponded with shifts in the areal percentage of particles in a sample plot covered with *C. demersum*. Two sites (island at RK 159.3 and RK 142.1) show dramatic temporal changes in only the lower portion of the surface grain-size distribution ($<D_{50}$) following the flood (Figure 12). Between years, the percent of particles associated with the macrophyte increased from 46% to 72% at the island at RK 159.3, and the site also had a larger proportion of finer sediment. Conversely, the percentage of particles associated with *C. demersum* decreased from 73% to 24% following the February 1996 flood, and
Figure 12. Surface grain-size distribution percentiles for island heads in the Primary Study Reach in 1995 and 1996.
far fewer finer particles were identified in the RK 142.1 sample plot. As a result, sorting at the islands at RK 159.3 and 142.1 changed dramatically between years (Figure 11).

*Primary Study Reach: Subsurface Grain-size*

Measurements of subsurface $D_{50}$ in the Primary Study Reach range from 6 mm to 52 mm (Figure 13), with an average of 22 mm. There is no clear trend in subsurface median grain-size with distance (Figure 13). The final statistical model shows no evidence for a longitudinal trend in subsurface $D_{50}$ values when temporal changes and macrophytes are accounted for in the Primary Study Reach (Table 2).

Following the February 1996 flood, subsurface material at eight of the twelve sites underwent fining, as shown by the reductions in $D_{50}$ values (Figure 13). For 3 of 4 sites where coarsening occurred, the $D_{50}$ value increases by less than 3 mm. However, the final statistical model shows no evidence for a temporal change in subsurface $D_{50}$ in the Primary Study Reach (Table 2). The data point representing the bar at RK 144.3 was influential in the regression. When removed from the analysis for comparison, there was strong evidence for a decrease in $D_{50}$ between years (2-sided p-value = 0.012). This underscores that the pronounced coarsening between years recorded at the bar at RK 144.3 was atypical. For sites where $D_{50}$ increased slightly, there was no clear pattern in the adjustments of other percentiles of the grain-size distribution. But for the eight sites where decreases in $D_{50}$ were recorded between years, fining tended to occur throughout the grain-size distribution.
Figure 13. Subsurface $D_{50}$ values for island heads in the Primary Study Reach. Pooled samples underwent statistical analysis. $D_{50}$ values for unpoled 1995 samples (volumetrically comparable to 1996 samples) are shown for comparison.
Primary Study Reach: Armoring

Armoring ratios range from 1.3 to 11.9, average 4.0, and generally decline with distance from the hydrocomplex (Figure 14). Multiple linear regression shows that there statistically significant evidence of a longitudinal trend in armoring (Table 2). The mean armoring ratio is estimated to be 0.16 less with each kilometer distance from the hydrocomplex, with a 95% confidence interval between 0.013 and 0.30.

Multiple linear regression also shows that there is suggestive but inconclusive evidence for an increase in armoring following the February 1996 flood (Table 2). Three upstream sites show the largest increases in armoring between years (Figure 14).

Data points representing the bar at RK 160.3 and the island at RK 158.0 in 1996 are influential in this regression. When the two points are removed separately or in combination (constituting three different scenarios of outlier removal), the decrease in armoring from the dam remains significant at the 0.05 level. In two of these scenarios, there is strong evidence for an increase in armoring between years. However, when only the point from the island at RK 158.0 in 1996 is removed, the temporal change is not significant at even the 0.1 level. Thus, the model is greatly influenced by these points. For this reason, the increase in armoring with time cannot be shown conclusively.

Entire Lower River

Over the lower river course, there was no evidence for a longitudinal trend in surface $D_{50}$, subsurface $D_{50}$ or armoring (Table 2, Figure 15). Surface bed material $D_{50}$ values and armoring ratios are not particularly large closer to the dam. In addition, the
Figure 14. Armoring ratios for island heads in the Primary Study Reach.
Figure 15. Surface $D_{50}$ values, subsurface $D_{50}$ values, and armoring ratios for island heads along the entire Lower Deschutes River in 1996.
Trask sorting coefficient shows very little difference in surface particle sorting between sites at this largest spatial scale (Figure 16). Thus, greater sorting was not observed in the Primary Study Reach relative to the lowermost river.

In each statistical model for the entire lower river, there are points influential to the regression. When three influential points in the final surface model were removed in seven combinations, no trend with distance remained for $D_{50}$ values in six of the seven cases. When three influential points were removed in seven combinations from the final subsurface model, there was no evidence for a longitudinal trend in four of the seven cases. In all three cases of distance becoming significant, the removal of the data point at the island at RK 144.3 led to a pronounced shift in the slope of the regression due to its high leverage. However, there was no basis for the removal of any of the points, so they were retained. For the final armoring model, when two influential points were removed in three combinations, the results did not change.

Tributary Particle Sizes

Most grain-size distributions sampled from fourteen tributaries are remarkably similar (Figure 17), with $D_{50}$ values averaging 49 mm and Trask sorting coefficients of about 1.7. Thus, most tributary sources of sediment do not supply distinctive sediment to the mainstem Deschutes, although $D_{50}$ values of tributaries are generally less than mainstem values (Figure 17).

The two largest tributaries, the Warm Springs and White Rivers, do have particularly distinct grain-size distributions. The White River, which drains fine glacial
Figure 16. Trask sorting coefficients for surface bed material at island heads in 1996 along the Lower Deschutes River. Higher coefficients indicate poorer sorting.
Figure 17. Surface grain-size distributions of fourteen sampled tributaries of the Lower Deschutes River. Thicker gray curves indicate the most distinctive grain-size distributions. Surface grain-size distribution of mainstem Deschutes (based on the pooling of all 1996 samples from island and bar heads) shown for comparison.
sediments and lahar deposits from the east side of Mount Hood, shows a strongly bimodal
distribution with a high proportion of material less than 2 mm (Figure 17). However,
there is no apparent trough in $D_{50}$ values in the mainstem Deschutes immediately
downstream of the White River confluence (Figure 18). Conversely, the Warm Springs
River has a relatively coarse grain-size distribution (Figure 17). Despite this, $D_{50}$ values
at downstream sites register no coarsening (Figure 18). Of the smaller, ephemeral
tributaries, Mud Springs Canyon (RK 12.4) has a particularly poorly sorted grain-size
distribution (Figure 17). Following a high-intensity rainstorm in July 1995, flash floods
in the canyon led to the deposition of a large alluvial fan, which constricted the channel
and formed a new rapid. Although the event was relatively recent and voluminous,
deposition of large particles in the mainstem was restricted to the fan formed a new rapid
in the adjacent channel. Some tributary inputs of coarse bed material apparently are not
transported far and, therefore, do not impose distinct changes in the mainstem
longitudinal surface particle sizes (Figure 18). Other sediment supplied to the channel
may be widely dispersed and not separately detectable.

Surface grain-size measurements taken just below Shitike Creek at the island at
RK 155.8 do not correlate well with grain-size distributions from Shitike Creek (Figure
19). Following the 1996 flood, mainstem gravels showed a predominance of particles in
the 5 to 30 mm range, which corresponds with mid-range grain-sizes for Shitike Creek.
Sorting coefficients for the island at RK 155.8 are more similar to those of Shitike Creek
(1.76) following the flood (1.48 in 1995 compared with 1.84 in 1996). However, some
gravels may have been derived from the mainstem bed. Thus, even where sediment has
Figure 18. Surface grain-size percentiles of the Lower Deschutes River in 1996 relative to tributary confluences. Location of tributaries indicated by vertical lines. $D_{50}$ values of tributaries shown by large squares.
Figure 19. Surface grain-size distributions from Shitike Creek and the island head at RK 155.8.
most likely been contributed to the mainstem from a tributary, tributary and mainstem
grain-size distributions are not closely linked.

**Within-Plot Spatial Analysis**

Two-dimensional semivariograms for 11 of the 12 sites in the Primary Study
Reach show no evidence for a gradient of particle size within sample grids. Points along
semivariograms constructed for the island heads at RK 159.3 and RK 149.7, for example,
tend to vary around a constant value (Figure 20). However, at the island at RK 142.1, the
lowermost sample site in the Primary Study Reach, there are increasing contrasts between
particle sizes with increasing lag distances up to 7 m (Figure 20). In particular, surface
particles separated by distances of less than 3 m are of similar size and are significantly
autocorrelated. The gradient was not evident in semivariograms constructed to detect
patterns exclusively in the x- or y-direction; this suggests that the gradient is arranged
diagonally across the sample grid at this site.

The Moran’s I correlograms also showed no evidence for spatial patchiness in all
12 sites in the Primary Study Reach, with no points extending beyond the 95%
confidence interval for determining statistical significance. Although not statistically
significant, the island at RK 142.1 again showed some evidence for autocorrelation
between points. The Moran’s I correlogram indicates that for lag distance less than 5 m,
as the distance between particles decreases, particles are increasingly similar in size and
are most alike at a lag distance of 1.9 m (Figure 21). At greater lag distances, no patches
are evident. The absence of a trough or a second peak in the correlogram (indicative of
Figure 20. Semivariograms for island heads at RK 149.7, 159.3, and 142.1 (arrayed in sequence for comparison with arranged results in Figure 22). Autocorrelation is apparent at lower lag distances at the island at RK 142.1
Figure 21. Moran’s I correlograms for island heads at RK 149.7, 159.3, and 142.1 (arrayed in sequence for comparison with arranged results in Figure 22). No points exceed the dotted lines indicating 95% confidence intervals for autocorrelation.
spacing between dissimilar and like patches, respectively) suggests that the patch of similarly sized particles extends beyond the size of the sample plot.

The source(s) of the minor spatial autocorrelation at the head of the island at RK 142.1 cannot be directly defined. However, the characteristics of the spatial pattern can be used to infer a possible key factor: the presence of *C. demersum*. To investigate this, results from the spatial statistics are compared to the actual data plots for the same three sites. Particles were coded based on particle size and the presence or absence of the macrophyte. In the absence of *C. demersum* as with the island at RK 149.7, grain-sizes are generally coarse with little sand (Figure 22). Conversely, at the island at RK 159.3 where *C. demersum* is dense and uniformly distributed, a larger proportion of finer particles (<2 mm) is apparent across the sample area. Finally, at the island at RK 142.1, *C. demersum* is distributed diagonally across the grid and is concentrated in the downstream-most river-right area. Within this area, the bed is finer, especially with particles less than 2 mm (Figure 22). The data also show that indeed the size of the patch of *C. demersum* extends beyond the size of the sample grid. At the island at RK 159.3, no gradient in the semivariogram or distinct peak in the correlogram is detected by spatial statistics, since the sample area is entirely contained within the patch of *C. demersum*.

Overall, grain-size patterns within these plots correspond well with the spatial distribution of *C. demersum*. Furthermore, the patterns of bed material size identified by spatial statistical methods match the arrangement of the macrophyte at each site.

When data from all 12 of the sample sites are compiled and the entire grain-size distribution is considered, the same correlation between grain-size and macrophytic
Figure 22. Planform plots of surface grain-size and macrophyte abundance for island heads at RK 149.7, 159.3, and 142.1. Vegetated island perimeters are positioned immediately to the right of each plot.
abundance is apparent. Increasingly finer particles are more likely to be associated with
the presence of the plant (Figure 23).

**Morphologic Analysis**

**Aerial Photographs**

Aerial photographs from the last four decades illustrate stable channel boundaries
and islands. Even at the confluences with the Warm Springs and the White Rivers, which
likely supply the largest volumes of sediment, photographs bracketing major flood events
did not reveal changes in planform geometry.

Islands and bars in the Primary Study Reach, however, typically grow or are
modified during large floods but undergo little change during intervening periods of time.
The supply of gravel from tributaries during these high flow events may play a critical
role in planform changes. Historical photographs show cycles of bar and island
construction at the confluence of Shitike Creek following the 1964 and 1996 floods,
which deposited large gravel bars, modified flow patterns, and reworked islands (Figure
24). Two large vegetated islands apparent from 1944 through 1956 probably represent
relic deposits from an older flood event when Shitike Creek injected gravels into the
mainstem. By 1968 (following the 1964 flood), the Shitike Creek fan was extended into
the Deschutes, the upstream island was completely eroded, and several lobate subaerial
bars were deposited. In addition, gravel apparently deposited during the 1964 flood filled
the side channel along an island further downstream (Figure 24). Similarly, following the
Figure 23. Matched bar graph showing proportion of particles in size classes in 1996 associated with *C. demersum* for all island heads in the Primary Study Reach.
Figure 24. Schematic showing major planform changes near Shitike Creek evident from aerial photographs. Darker shapes indicate islands. Lighter shapes are subaerial bars.
1996 flood, coarse lobate gravel bars formed along the downstream end of this island at RK 155.8 and midchannel aggradation occurred (noted during field sampling) between the two remaining prominent islands. Additionally, it was noted in the field that the side channel alongside the downstream-most island was nearly blocked by deposited gravels. Thus, during both the 1964 and 1996 floods, major morphologic changes were similar in nature and location.

Only a few other changes in island morphology were noted in the historical photographic record of the Primary Study Reach. The 1944 and 1956 photographs show an island along the river left side at the downstream end of an expansion zone below Dry Creek (RK 151.4). In 1968, this feature appears to be a small, emergent gravel bar. Today, there is a submerged bar at this position. Thus, the feature had been reduced in elevation during the record, but remains a depositional zone. No obvious changes were noted in this zone following the 1996 flood. From at least 1944 to the present an island situated at the upper end of this widened section has persisted, so changes have been extremely localized. Photographs of the lowermost river are too sparse to correlate any changes with high flow events.

Huntington (1985) argues that islands near the hydrocomplex have provided a natural source for gravel recruitment that has partially offset losses in sediment supply. Photographic analyses (in conjunction with field observations) could neither substantiate nor refute this claim. Overhanging vegetation and the scale of photographs makes it impossible to discern such small changes in island size at most sites. Vegetation, once established, probably acts to stabilize an island and minimize gravel export.
Historical Cross-Sections

Comparison of historical cross-sections reveals that small-scale bed adjustments occur frequently but do not follow a clear trajectory. Cross-sectional perimeter and width have changed little over the 39-year time span for the one gage site studied (Figure 25). However, there appear to be peaks in both the maximum depth and cross-sectional area associated with major flooding events. When compared with the timing of the six largest flow events during this period, three of the four largest events are associated with the largest shifts in maximum depth and area (Figure 25). There is no evidence for increasing channel degradation with time; following flood events, maximum depths and areas approach pre-flood values within days.

Repeated downward and upward shifts, generally less than 1 m, of the channel bed elevation are apparent. The comparison of individual cross-sections suggests that scour is commonly distributed across the channel bottom, but typically reaches a maximum in the thalweg (Figure 26). The most striking changes are associated with flood events. The February 1958 event is associated with some of the lowest bed elevations at the river left portion of the cross-section (Figure 26). Subsequently, the channel bed refilled across the section. Between early November 1964 and late December 1964 the entire channel bottom was lowered by 0.1 to 0.5 m. In the years following the 1964 flood, aggradation on the river right portion of the cross-section returned the bed to its pre-flood elevation. However, the river left portion, where scour was most pronounced, adjusted upwards gradually to pre-flood levels. The flood of record in February 1996 caused channel scour exceeding 1 m to a low point along the
Figure 25. Maximum depth, width, perimeter, and cross-sectional area relative to fixed datum at cross-section in Primary Study Reach following dam construction. Vertical lines represent large flood events (mean daily flow >340 cms) in February 1958, December 1964-January 1965, March 1972, February 1982, and February 1996.
Figure 26. Historical cross-sections taken at USGS cableway in Primary Study Reach. The lowest elevation is set at zero. The fixed datum from which cross-sectional properties were compared is shown by the dashed horizontal line.
river right and at the lowest levels observed since 1958 on the river left (Figure 26). In the year following the 1996 flood, aggradation along the entire channel bed occurred. Overall, the data do not record gradual degradation of the channel bed near the dam.

Fluctuations in depth and cross-sectional areas are related to high discharge events. There is a rough correspondence of area and maximum depth to instantaneous discharge (Figure 27). Particularly large cross-sectional areas and depths are associated with flows exceeding 275 cms. Since these areas and depths are all calculated for below a common elevational datum, the fluctuations are not a result of the hydraulic geometry of the river.

Channel bed adjustments such as these observed near the Pelton Round Butte Hydroelectric Project are apparently characteristic of other similar straight reaches of the Lower Deschutes River. Analysis of cross-sections at Moody further downstream illustrate similar cycles of scour and fill associated with the two largest flood events in 1964 and 1996. In this lower reach, scour during high flow events can reach up to 1.5 m, but refilling of the scoured zone can occur within days of a flood peak. Following these two largest floods, aggradation occurred and returned the bed to within its pre-flood range of elevation.

Field Observations

In general, flood impacts were relatively minor in the Primary Study Reach. However, two islands (one of which was the island at RK 155.8) underwent significant morphologic change. At both of these sites, flow competence dropped in response to local increases in channel width. As a result, emergent bars adjacent to the island
Figure 27. Maximum depth and cross-sectional area below fixed datum versus instantaneous discharge for the USGS cross-section in the Primary Study Reach.
aggraded. Other changes to islands include erosion along the sides (RK 159.3), scour and gravel transport over the surface (RK 147.7), and erosion along the head (RK 155.8 and RK 149.7). Field observations documented erosion along many islands, particularly the island at RK 159.3, where dense root systems defend the bank. Erosion along this island has been chronic since at least the mid-1960's (Huntington 1985). Extended zones of bank erosion along the Lower Deschutes were generally rare. Bank erosion was most pronounced along loose, sandy banks of the outer river bend below the Shitike Creek confluence. Other field studies suggest that bank erosion affects only about 2.0% of the lowermost 111 river kilometers and is largely a result of natural causes (Klingeman et al. 1990).

Although spatially variable, flood impacts were more pronounced in the lowermost section of the Deschutes River below the Warm Springs and White Rivers. Localized gravel deposits were extremely loose and were deposited with steep angles of repose along bars and islands emergent at low flows. Complex depositional patterns formed around island vegetation in response to hydraulic sorting of bed material and scour by flow. Patches of floodplain and island vegetation were commonly abraded, broken, or completely uprooted and transported downstream. Island heads were especially vulnerable to erosion and stripping of vegetation, since they encountered high-velocity, mid-channel flood waters and floating debris.
DISCUSSION

Longitudinal Analysis

The data indicate that there is no clear longitudinal pattern in the surface and subsurface bed material in the Primary Study Reach and in the entire lower river. Pebble counts, in particular, provide an accurate description of surface bed material size. Data points obtained from the same site for different years are generally similar to each other but different for $D_{50}$ values at other sites in the Primary Study Reach. For this reason, the finding of no longitudinal pattern in surface $D_{50}$ values cannot be attributed to sampling error. The range in $D_{50}$ values from all bar and island heads on the lower river is comparable to that observed in multiple environments surrounding the same island. This further suggests that small differences in the grain-size distribution between sites could be in part explained by differences in local hydraulics between sites on the Lower Deschutes River.

Low adjusted $R^2$ values for all statistical models (0.02 to 0.23) suggest that factors other than downstream distance and year are much more important in determining bed material properties. The marked uniformity of grain-sizes and armoring over the extended river course is partially reflective of the lack of major changes in channel slope, the grain-size range of bed material introduced by tributaries, and the nature of hillslope inputs. There have been no strong external influences in the lower river system over the past half century. As a result, there have been relatively few perturbations to the grain-
size distribution or channel morphology that could shift the channel away from near-equilibrium conditions.

Inputs of bed material from tributaries do not produce clear peaks or troughs in the grain-size distribution of the Lower Deschutes River. No contrast is noted between reaches upstream and downstream of major tributaries, where one might expect changes in longitudinal patterns of bed material properties with partially replenished sediment supply. There are several factors that may inhibit textural shifts at the confluences of the White and Warm Springs rivers. Suspended sediment transport in the lower White River increases substantially from September and October (540 tons/month) to November and December (59,422 tons/month; unpublished data as reported by U.S. Department of Energy 1985). Thus, although the tributary presumably transports material during high-flow events, much of this material may be suspended sediment which is flushed through the drainage, so that the bed of the Deschutes is not noticeably finer downstream of the White River. Cameron and Major (1987) made similar observations in the Upper Deschutes River, where downstream bank erosion was accelerated subsequent to the operation of Wickiup Dam in 1943. The authors argue that this fine-grained sediment probably has a short residence time and is transported through to the next reservoir. Since transport rates are directly related to discharge, fine sediments are even more likely to be transported through the Lower Deschutes River or to be deposited as beaches and marginal deposits, rather than mixed with the bedload surrounding islands and bars. In support of this, many sandy marginal deposits were noted downstream from the White River during the course of field reconnaissance. The Warm Springs River forms an extensive, coarse fan at its confluence with the Deschutes. Coarser bed materials of the
Warm Springs may be transported extremely infrequently through this low-gradient section and instead be deposited within the fan complex.

In contrast, some inputs of gravel from Shitike Creek may be deposited locally within the Deschutes mainstem, inducing morphologic and only minor textural shifts on the mainstem. That such shifts following a 100-year flood event are only noted in the area immediately downstream of the confluence suggests that some bed material was input from Shitike Creek. These morphologic changes are similar in nature and location to previous changes as interpreted from the photographic record. The episodic delivery of gravel from debris flow events in canyons over the longer term may be responsible for many of the large inputs of material into the mainstem, such as those which evolved into islands. The deposition of debris flow material and the persistence of debris flow deposits near canyon mouths demonstrate the limited movement of sediment inputs.

There is some statistical evidence for especially high armoring ratios (up to 11.9) near the hydrocomplex and after the 1996 flood in the Primary Study Reach. The increase in armoring between years was produced by subsurface fining, and the surface layer did not change significantly between years. The apparent increase in armoring via subsurface fining is contrary to models of armor development. If sediment supply below the dam was substantially reduced, one would expect selective erosion to cause downstream winnowing of bed material. This, as our conceptual model suggests, would cause the surface grain-size to coarsen with time near the dam and for the front of coarsening to prograde downstream, particularly during high flow events. If changes in the size of subsurface bed material are considered to indicate shifts in sediment supply, then the observed post-flood reduction in subsurface grain-size could
suggest that erosion of channel backs and islands by flood waters introduced fine material into the bedload. However, no apparent or adequate source of fine sediment exists in this reach nor in the bed. Suspended sediment stirred up by flood waters just below the hydrocomplex is not likely to have contributed much material to downstream sample sites. Furthermore, fine sediment mobilized in the Primary Study Reach during the February 1996 flood is unlikely to have been mixed throughout the subsurface layer at the majority of sample sites with no influence on the surface bed material.

The most probable explanation for the fining of subsurface bed material between years is that it resulted from the reduction in the volume of subsurface bed material sampled between years. Ferguson and Paola (1997) found that in small bulk samples, all percentiles, including the median, are underestimated, since it is less likely for a large clast to be included. While good precision in the sample mean can be achieved with sample sizes less than those suggested by DeVries (1970) and Church et al. (1987) for moderately sorted material, the phenomenon is especially serious for smaller samples of poorly sorted material like fluvial gravels (Ferguson and Paola 1997). The relatively consistent lowering of all percentiles at sites in the Primary Study Reach strongly suggests that the reduction of sample volume from an average of 60.9 kg to 20.3 kg may have caused the observed decrease in subsurface material size. To test this, multiple $D_{50}$ estimates taken from unpoled bulk samples at a site in 1995 were compared to samples taken in 1996, since they are equivalent volumetrically. If there is indeed bias resulting from the change in sample volumes between years, then the multiple $D_{50}$ values estimated individually from each bulk sample from a site in 1995 should be less than the one $D_{50}$ estimated from the pooling of these same bulk samples. This phenomenon was not
substantiated (Figure 13). But since most $D_{50}$ values from samples taken in 1996 fall within the range of comparably sized, unpooled 1995 $D_{50}$ values, there is no clear evidence for subsurface fining between years. For this reason, there may be no physical basis to spatially correlate the three high armoring ratios measured near the dam with the dam itself. In support of this, when only the 1996 data are considered over the longer river (so that subsurface samples are of comparable volumes), neither surface $D_{50}$ values, subsurface $D_{50}$ values, or armoring ratios illustrate a longitudinal trend (Figure 14, Table 2).

Following the criteria of Church et al. (1987), the requisite size of a representative bulk sample of the subsurface material may be estimated by the largest particles in the surface population, as long as the surface constitutes the same deposit. Using the average surface $D_{95}$ value of 150 mm for sites in the Primary Study Reach, the proposed 0.1% of sample size for the largest clast would then require a sample weighing about 5,000 kg per site. Even using a relaxed criterion of 5% would still require 100 kg of bed material. The labor involved in transporting this sediment from the river and the laboratory time required to process such samples would be overwhelming. Thus, the precise description of grain-size distributions of bulk samples remains a difficult problem in such studies of gravel-beded rivers.

**Morphologic Analysis**

On the Lower Deschutes, scour and fill occurs in response to flood events exceeding 275 cms (Figure 27). At lower discharges, cross-sectional areas and maximum
depths are much smaller and more variable. These results imply that most bedload is transported during flows greater than 275 cms, as during the 1964 and 1996 floods. Similarly, major morphologic responses on the Lower Deschutes noted in aerial photographs generally are associated with only these anomalously high flow events. Because flows of the Lower Deschutes during the past 30 years have exceeded 275 cms less than 1% of the time, this also suggests that sediment transport rates are very low over decadal time scales. This inference is supported by bedload transport modeling indicating very infrequent mobilization of bed material (~25 days since 1923) on the Lower Deschutes River (Fassnacht 1997). It is estimated that more than 70 percent of this movement occurred during the February 1996 flood (Fassnacht 1997).

There is likely much spatial variability with channel bed adjustments, so cross-sectional responses at this site can not necessarily be generalized to the entire Primary Study Reach. However, the cross-section at the Madras gage responds strikingly similarly, though to a smaller magnitude, as that at the cross-section near the confluence with the Columbia River. Furthermore, in the Upper Deschutes below Wickiup Dam, there is no evidence for changes in the location or size of gravel bars or in the vertical stability of the channel bed, although some bank erosion has contributed fine sediment (Cameron and Major 1987). Finally, the inspection of aerial photographs indicates that most zones of the river are stable. Thus, there is no evidence that any morphologic responses immediately below the dam have increased relative to the overall river.

Overall, little change in channel morphology was noted in aerial photographs and historical cross-sections, which represent a time series extending over 70 years. It is
conceivable that the threshold for larger scale geomorphic change has yet to be reached, but could occur over a longer time scale.

**Within-Plot Spatial Analysis**

Initially I sought to account for the influence of macrophytes on the grain-size distribution at individual sites, so that larger scale textural patterns could be examined. However, in the course of this analysis many interesting links between *C. demersum* and the surface bed materials were revealed.

The establishment of *C. demersum* on the Deschutes River probably owes to feedback loops between its ecology, surface bed material, hydraulics, and sediment transport. It is suited to colonize shallow, low-velocity zones where its shoots extend into the sand and finer gravel. As it grows toward the water surface and exerts boundary roughness on flows, it may trap fine organics and suspended sediments, as was apparently observed in several sample plots during the 1995 and 1996 summers. During higher winter flows and cooler winter temperatures, however, stalks of the macrophyte either die off or are stripped away, and only the mats of shoots remain within the surface armor layer. These networks of shoots hold bed material that would otherwise be transported downstream, thereby preserving the medium required for its survival. Silt particles accumulating at the base of the plants during the summer are probably transported downstream once the stalks are gone.

Within individual sample plots, there is a strong correlation between patches of finer sediment and the spatial arrangement of *C. demersum*. As the areal cover of the
macrophyte increases, the overall surface $D_{50}$ is more likely to decrease. In the Primary Study Reach, *C. demersum* traps sand in an otherwise sand-poor environment. This may shift the sediment transport regime, causing larger volumes of sand stored during the summer within the stalks to be transported during winter flows. Similarly, in the Upper Deschutes above the Pelton Round Butte Hydroelectric Project and its reservoirs, sand is trapped in dense patches of the macrophyte *Elodea sp.* but released upon death or physical disruption (Cameron and Major 1987).

There are many direct and indirect impacts downstream of hydroelectric power developments that can impose ecological changes for macrophytes. River regulation tends to dampen seasonal fluctuations in discharge, decrease turbidity, and change water temperature, thereby reducing the range where some aquatic plants may live and providing ideal conditions for some species (Nilsson 1978). Many studies report changes in macrophyte populations following river flow changes owing to impoundment or diversion (Hall and Pople 1968; Holmes and Whitton 1977; Nilsson 1978; Rørslett 1989; Petts 1984a; Nilsson et al. 1997; French and Chambers in press). Once established, macrophytes alter channel roughness and flow parameters (Watson 1987).

No evidence exists to document changes in *C. demersum* following construction of the hydrocomplex. Huntington (1985) claims that long-time residents of the Deschutes basin have indeed noted a greater abundance and distribution of macrophytes since dam construction. Higher concentrations of the macrophyte observed in the Primary Study Reach compared with further downstream suggests that it may have invaded and flourished in this area. One might expect that lower flows (and thus lower depths and shear stresses) would encourage the growth of this macrophyte, since light would more
easily reach the plant and it would encounter lesser erosive forces. However, monthly flows have generally been higher in the post-dam time period, except for in April (Huntington 1985), so it is unlikely that a shift in discharge could explain its growth. Other channel properties such as turbidity and temperature are beyond the scope of this study. Huntington (1985) suggests that with thalweg deepening, aquatic plants encroaching along the channel margin could limit the usability of bed materials by fish. In this study, there is no evidence for such post-dam shifts in channel geometry, and these ecologic effects are not well understood.
REVIEW OF CONCEPTUAL MODEL

In this study, it was hypothesized that low sediment transport rates over the longer term have limited textural and morphologic adjustments of the Lower Deschutes River. Morphologic and textural analyses show no progressive spatial or temporal pattern to channel response following river impoundment. The results suggest that there is low sediment supply from tributaries and bedload transport is infrequent. Thus, as Figure 1 illustrates, the channel bed is prone to either textural adjustment or no change, but major morphologic changes are highly unlikely.

Furthermore, if flows and the supply of sediment change little after impoundment, textural patterns downstream from the hydrocomplex should be absent (Figure 2b). As hypothesized, results from this study indeed indicate limited, if any, textural and morphologic changes along the Lower Deschutes. Short-term adjustments of the channel bed elevation occur during only high flows (>275 cms), which have occurred very infrequently during the period of record. This suggests that sediment transport rates are low over the longer term. For this reason the ratio of change in sediment supply following impoundment, represented by the ordinate in Figure 2, may be close to one.

The minor hydrological changes noted in the flow record since regulation suggest little change in the frequency of bed-mobilizing flows. In conjunction with the relatively small decline in sediment supply, this suggests that the Deschutes may represent a zone between Cases B and D in Figure 2. Any grain-size trends on the Lower Deschutes are of small spatial extent and magnitude relative to textural patterns observed on other large, dammed river systems. The most striking textural patterns, in fact, may be due to the
local abundance of macrophytes on the bed surface, rather than larger scale factors like distance from the dam or time since a large flood.

Other studies of large dammed river systems also tend to support the conceptual model illustrated by Figure 2. Among these rivers, however, the Lower Deschutes River apparently represents an unusual case. Since on most rivers dams markedly impact either or both the frequency of competent flows and the sediment load, grain-size patterns such as those in Cases A, C, and D are documented.

For example, the Peace River in British Columbia and Alberta may represent end-member A in the conceptual model. Even before impoundment, the majority of bed material in the Peace River entered below the current point of regulation. Since dam construction, peak flows have been dramatically decreased, but the supply of sediment has not been reduced except for that comprising the mainstem bed and banks (Church 1995), making it illustrative of Case A. There has been no degradation (since flow is no longer competent to move the gravel and cobble bed), aggradation is apparent at tributary junctions, and fine sediments supplied from tributaries are being deposited along the channel perimeter (Church 1995).

Case D is exemplified by the Snake River. Annual flood series below the Hells Canyon Complex show no significant change in the size or frequency of floods; however, the winnowing of finer bed material has led to bed degradation and the loss of 75% of the surface area of sand beaches (Collier et al. 1996).

Most commonly, dramatic reductions in both sediment supply and competent flows lead to armoring, coarsening, and degradation of the channel bed (Williams and Wolman 1984, Galay et al. 1985), as in Case C. In the first two months following closure
of the dam at Cochiti on the Rio Grande River, most bed material less than 1 mm in
diameter was eroded (Dewey et al. 1979). Three years later, increases in the median
diameter of the surface bed material ranged between about 2 and 5 times pre-dam sizes
and extended 19 RK downstream (Lagasse 1994). Within 7 years, this front of coarsened
surface bed material extended another 13 RK further with local increases in $D_{50}$
exceeding a factor of 20.

Channel responses are complex in time and space, and are typically studied on a
case-by-case basis. While specific impacts following river impoundment have been
described, there has been less synthesis of how channels can be predicted to respond to
changes in sediment supply and the frequency of bed-mobilizing flows. The conceptual
model suggested here successfully predicts a range of responses to channel impoundment
in a geomorphic context. Many studies of other rivers document armoring and
degradation of the channel bed due to reduced sediment supply where flows are still
competent to move a large portion of the bed material, such as where sand is prevalent.
In contrast, the Deschutes River represents a unique hydrologic and sedimentologic
environment where sediment supply and transport may be limited over time scales greater
than the historical flow record.
CONCLUSIONS

Qualitative geomorphic analysis is an important analytical technique in assessing river responses to dam construction. Although portions of this study were conducted separately, results from particle size measurements, aerial photographs, and historical cross-sections are mutually supportive and all point in the same direction. The lack of convincing longitudinal trends before and after the record February 1996 flood suggests that neither dam construction nor major flood events resulted in significant channel bed adjustments. In this setting tributaries play a role in morphological dynamics by partially offsetting low sediment supply. However, even where Shitike Creek injected gravels into the mainstem Deschutes, sedimentological changes were minor and grain-size distributions did not change significantly.

The 1996 flood mobilized significant fractions of the bed material in the Deschutes River; however, little change in median grain-size was observed in the study reach or the entire lower river. The absence of pronounced channel change following the flood event of record suggests that even during this event, sediment transport rates were relatively modest. Thus, the frequency of bed-mobilizing flows has been historically low and has changed little following impoundment. This further implies that there have been historically low sediment transport rates. In addition to the limited flow competence, the Deschutes has limited sediment supply. Large volumes of sediment are only rarely contributed to the mainstem by perennial tributaries and debris flow events. Due to its geologically-driven uniform flow regime and absence of many sediment sources, the Deschutes River is an unusual regulated river system. More dramatic adjustments of the
bed material and elevation may occur over the longer term as flows exceeding those of the historical record mobilize greater volumes of the bed material. However, the modest inputs of sediment may keep pace with the low rates of sediment transport on the Lower Deschutes. The longitudinal analysis suggests that armoring and degradation below dams may be limited where sediment transport rates are low and the sediment supply is limited.
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