SPATIAL DISTRIBUTION OF IMPACTS TO CHANNEL BED MOBILITY DUE TO FLOW REGULATION, KOOTENAI RIVER, USA

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Abstract The regulated hydrograph of the Kootenai River between Libby Dam and Kootenay Lake has altered the natural flow regime, resulting in a significant decrease in maximum flows (60% net reduction in median 1-day annual maximum, and 77%-84% net reductions in median monthly flows for the historic peak flow months of May and June, respectively). Other key hydrologic characteristics have also been affected, such as the timing of annual extremes, and the frequency and duration of flow pulses. Moreover, Libby Dam has impeded downstream delivery of sediment from the upper 23,300 km^2 of a 50,000 km^2 watershed. Since completion of the facility in 1974, observed impacts to downstream channel bed and bars in semi-confined and confined reaches of the Kootenai River have included coarsening of the active channel bed, homogenization of the channel bed, disappearance of relatively fine-grained beach bars, and invasion of bar surfaces by perennial vegetative species. These impacts have led to reduced aquatic habitat heterogeneity and reduced abundance of candidate recruitment sites for riparian tree species such as black cottonwood (*Populus trichocarpa)* and native willows *(Salix spp.).* Limited quantitative documentation of the pre-regulation substrate composition exists. However, based on the existing evidence assembled by others, we have assumed that the contemporary river bed is relatively coarser than the pre-regulation bed. Making this assumption, we tested the hypothesis that even though the contemporary bed is relatively coarser than the historic bed condition, the pre-regulation hydrograph applied to the contemporary bed would result in 'regular' bed movement in most sections of the study reach, while the regulated hydrograph provides limited opportunities for bed and bar adjustment. Our sampling effort to document the contemporary bed composition over a 100-kilometer channel section included stratification of the study reach by reach-scale characteristics, and underwater photography-based methods. We present the results in a spatially-distributed manner that allows evaluation of both local factors and downstream trends in hydrologic alteration through the study reach.

INTRODUCTION

Basin Description and Management History The Kootenai Basin (Fig. 1) is an international watershed (spelled Kootenay in Canada, Kootenai in the U.S.) originating in the northern Rocky Mountains of eastern British Columbia, Canada. From the headwaters, the Kootenai River flows south into Libby Reservoir whose 145-km length straddles the Canada-USA border (Hoffman et al. 2002). From Libby Dam, the river flows through Montana, Idaho and back into British Columbia before emptying into Kootenay Lake. Located 357.1 river kilometers above the mouth, Libby Dam and Reservoir is a 130-m high flood control and hydropower production facility that impounds flows originating in the upper 23,300 km^2 of a 50,000 km^2 basin. Kootenay Lake is a naturally formed lake whose levels have been regulated following deepening of the outlet and construction of Corra Linn Dam near Nelson, British Columbia in the 1930s (Army Corps of Engineers 1984).

The natural flow regime for the Kootenai River sustained peak flows in late spring, followed by a gradual recession to base flow by September, and low winter flows (Hoffman et al. 2002), a pattern typical of snowmelt-dominated basins in western North America (Poff and Ward 1989).

The Lower Kootenai Basin has been intensively managed starting in the late 1800s. Perturbations have included: floodplain diking, drainage and conversion to agriculture over approximately 21,000 hectares between Bonners Ferry and Kootenay Lake (1900-1940s), channel dredging coincident with floodplain diking (1900-1940s), completion of Corra Linn Dam (1932), dredging of the natural Kootenay Lake outlet upstream of Corra Linn Dam (1930s), an international treaty signed to increase winter levels and decrease spring levels in Kootenay Lake, impacting natural backwater profiles to Bonners Ferry, ID (1938), and completion of Libby Dam (1974).

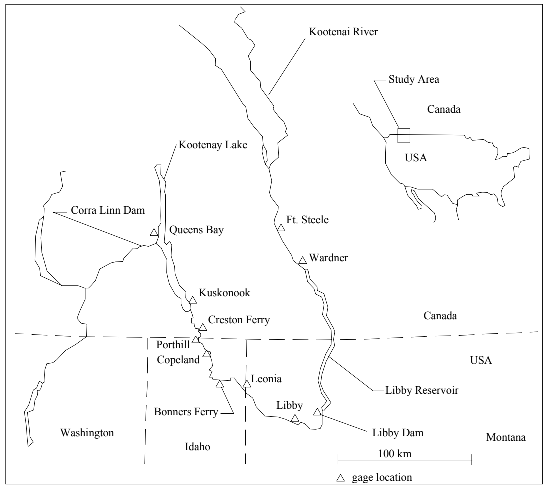

Figure 1 Location map showing the Kootenai River Basin, with gaging station locations indicated.

Several adverse impacts to the aquatic and riparian ecosystems have been attributed to the operation of Libby Dam. These impacts include declines in recruitment of native fish, such as white surgeon (*Acipenser transmontanus*) and burbot (*Lota lota*) (Hoffman et al. 2002), and disruption in recruitment of black cottonwood (*Populus trichocarpa*) and native willows *(Salix spp.)*, key structural elements in riparian forests in the region (Polzin and Rood 2000) . Because the native ecosystem served as the basis for the subsistence economy of the Kootenai people historically, the long term sustainability of the indigenous culture is directly linked with the fate of these species and that of other related species. Therefore, an assessment of ecosystem losses due to Libby Dam and Reservoir operations is currently being led by the Kootenai Tribe of Idaho in cooperation with several government and non-government entities, and supported by the Bonneville Power Administration. The analysis presented here is a part of this larger effort.

Ecological Significance of Channel Bed Mobility Periodic channel bed mobilization events that occur as part of a natural flow regime have been shown to be crucial to the sustained, long-term health of river and floodplain ecosystems (Poff et al. 1997). In particular, disturbance of the channel bed and banks during maintenance flows (near-bankfull events for coarse-grained rivers (Schmidt and Potyondy 2004)) can recruit fresh sediment from alluvium stored within the channel bed and floodplain that maintains fish spawning substrate and invertebrate habitats (Poff et al. 1997). These flows also maintain diverse aquatic habitat conditions (Poff et al. 1997) and provide suitable recruitment sites for riparian tree species (Rood and Mahoney 1990, Braatne et al. 1996) In regulated rivers, the combined impacts of reduced sediment transport capacity and reduced downstream sediment delivery have been shown to lead to coarsening of the channel bed, simplification of channel morphology and instream habitats, degradation of spawning materials (Williams and Wolman 1984, Ligon et al. 1995) and limitation of riparian succession (Rood and Mahoney 1990, Braatne et al. 1996), among other impacts. In the case of the Kootenai River downstream of Libby Dam, prior researchers have suggested that flow regulation has significantly reduced the abundance of candidate recruitment sites for black cottonwood trees (*Populus trichocarpa*) and native willows *(Salix spp.),* and led to the colonization of remnant bar surfaces by perennial grasses (Polzin and Rood 2000, Jamieson and Braatne 2001), led to a loss of habitat heterogeneity (Paragamian 2002), led to persistence of depositional deltas at tributary junctions (Marotz et al. 2001, Dibrani 2003, Zelch 2003), and led to reduced mainstem aquatic habitat quality for fish and invertebrates (Hauer and Stanford 1997, Marotz et al. 2001).

Background for Assessment of Impact of Flow Regulation on Bed Mobility Only qualitative evidence of the pre-dam substrate condition is available. This evidence consists of early timber survey notes, historic aerial photos and the recollection of local residents, which suggest an abundance of fine-grained bars along the channel margins in the study reach. There is a deficit of similar bars under current conditions (Polzin and Rood 2000). We therefore assume that prior to Libby Dam construction, a greater supply of fine-grained sediment was supplied to the study reach through delivery from upstream sources (now trapped in Libby reservoir) and recruitment from local sources through channel disturbance and migration during periodic high flow events. Further, the current operational regime is characterized by lower, yet much more frequent, peak flows (hydropeaking), which has likely resulted in selective withdrawal of the finer portion of the substrate distribution (i.e. winnowing (Burke In preparation). Based on this line of reasoning, we have assumed that the contemporary river bed is relatively coarser than the pre-regulation bed. Making this assumption, we tested the hypothesis that even though the contemporary bed is relatively coarser than the historic bed condition, the pre-regulation hydrograph applied to the contemporary bed would result in 'regular' bed movement in most sections of the study reach, while the regulated hydrograph provides limited opportunities for bed and bar adjustment. Comparison of the mobility of the contemporary bed materials under pre-dam and post-dam flow regimes will give an estimate of the impact of flow regulation on channel bed mobility.

To evaluate the impact of reservoir operations on the spatial and temporal pattern of bed mobility, we conducted incipient motion-based calculations spaced over a 90.8 km river reach (River km 249.7-340.5). We assessed the relative ability of the pre-dam and post-dam flows to move the post-dam median bed surface grain sizes (D_{50}). Based on evidence of channel armoring, we assumed that the surface sediments were limiting with respect to bed mobility in our evaluation.

IMPACTS OF REGULATION ON DOWNSTREAM HYDROLOGY

As indicated above, the natural flow regime for the Kootenai River sustained peak flows in late spring, followed by a recession to base flow by September, and low winter flows. The hydrologic regime of the Kootenai River has shifted significantly since the completion of Libby Dam. See Figure 2 (Dibrani 2003).

In order to assess the degree of hydrologic alteration caused by the facility, the long-term time series for seven mainstem gages were correlated using the methods of Searcy (Searcy 1960) and evaluated using the Indicators of Hydrologic Alterations (IHA) methodology (Richter et al. 1996, Richter et al. 1997, Richter et al. 1998) and software (Nature Conservancy 2003). In their 2003 analysis, Olden and Poff found that the suite of indices resulting from the IHA method adequately characterize the principal components of flow regimes (Olden and Poff 2003). When pre-dam and post-dam periods are analyzed, the subsequent hydrologic alteration due to the dam's operations can be evaluated.(Richter et al. 1996, Richter et al. 1997). By conducting this analysis for multiple gages throughout a drainage basin, the spatial distribution of the alteration can be assessed (Richter et al. 1998).

The composite time series for the free-flowing Water Survey of Canada gage Kootenai River at Wardner was used as an unregulated control in this analysis. The other six gages included in the analysis are USGS gages Kootenai River below Libby Dam, and Kootenai River at Libby, Leonia, Bonners Ferry, Copeland and Porthill. Figure 3 shows the distribution of the magnitude of change in median monthly and annual flows through the study reach. As can be seen the relative magnitude of hydrologic alteration due to climate change and other factors as determined at the Wardner gage is small when compared to the hydrologic alteration downstream of the dam site. It is also evident that little attenuation of the alteration occurs with successive tributary inputs. The greatest magnitude alterations occur during the high flow months of May-July (-360-900cms) and the low flow months of November-January (+330-470 cms). Strong patterns of increased peaking with decreased peak durations were also among the indications of the IHA analysis. These patterns are indicative of an inverted annual hydrograph with hydropeaking, and are consistent with the facility's dual objectives of flood control and hydropower generation (Burke In preparation).

IMPACTS OF REGULATION ON DOWNSTREAM SEDIMENT SUPPLY

Libby Reservoir has also affected downstream sediment supply. Given its long (145 km) and narrow configuration, the reservoir traps virtually all sediment (Tetratech 2004) that originates from the upper 23,300 km^2 of the 50,000 km^2 watershed. During the design of the Libby Project, the Army Corps of Engineers estimated the trap efficiency of the reservoir at greater than 90 percent (Army Corps of Engineers 1971). The disruption in downstream sediment delivery is qualitatively evidenced by the abundance of fine-grained beach bars above the reservoir in the unregulated reach and the absence of the same below Libby Dam. Long-term residents of Libby, Montana have indicated that such bars were abundant in the reach below the dam prior to Libby Dam construction. (Polzin and Rood, 2000).

As part of our substrate sampling effort, we assessed the degree of armoring at four mid-channel bar locations in the study reach. Using a technique developed by Buffington (Buffington 1996), we first conducted a pebble count on the bar surface using a 1-m^2 sampling grid frame. After removing the surface particles, we then manually mixed the subsurface materials, replaced the sampling frame over the same area, and repeated the pebble count of the subsurface particles. We found that the ratio of surface to subsurface median grain size ($D_{50surface}/D_{50subsurface}$) ranged from 2.0 to 5.3 in the study reach, with the larger ratios occurring with increased distance from the dam, similar to what has been observed for regulated reaches of the upper Colorado River (Pitlick and Cress 2002). These ratios indicate a moderate degree of armoring. This may suggest limited sediment supply from upstream sources, but does not provide conclusive quantitative evidence of disrupted sediment supply. The effect of the sediment trapping by the dam may be moderated by tributary inputs occurring between the dam and the sample locations, and reduced bed sediment transport capacity as a result of dam operations. The impact of these factors on sediment supply to the study reach was not explicitly evaluated as part of the analysis summarized in this paper.

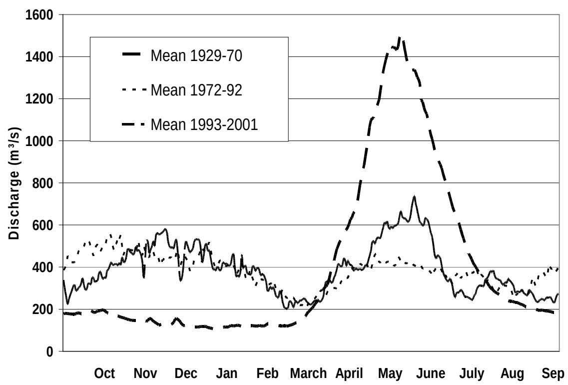

Figure 2 Timing and magnitude for Kootenai River flows at USGS gage # 12305000, Kootenai River at Leonia, adjacent to Idaho-Montana state boundary.

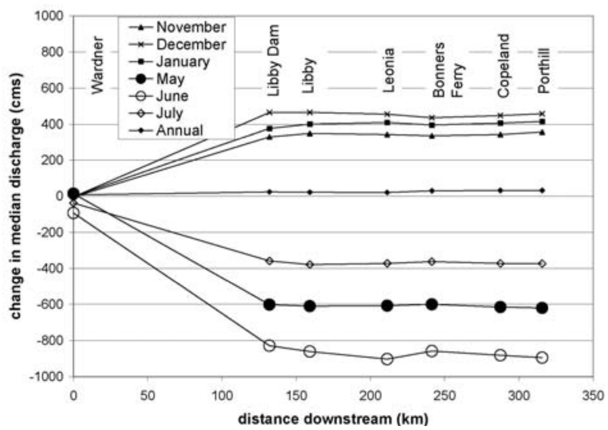

Figure 3 Change in the magnitude of median monthly and annual flows for 7 mainstem Kootenai River gaging stations based on comparison of pre-dam (1939-1967) vs. post-dam (1975-2002) time series.

CHARACTERIZATION OF BED SURFACE SUBSTRATE

For our substrate sampling effort, we segregated the Kootenai River between Libby Dam (River km 357.1) and Bonners Ferry (River km 246) into 11 sub-reaches based on reach-scale characteristics of slope, morphology, valley width, and channel confinement (eg. Montgomery and Buffington 1997). Ten of the eleven reaches match the 'canyon' morphology described by Snyder and Minshall (Snyder and Minshall 1996), while the eleventh reach corresponds with their 'braided' morphology. Of the eleven reaches, we were unable to sample 4 reaches due to navigation hazards at the time of sampling. The unsampled reaches include 3 short reaches over a 10.8 km length (River km 307.4 to 318.2) adjacent to Kootenai Falls, and the Libby Dam tailwater reach (River km 357.1 to 345).

Within each reach, we sampled surface sediment along transects placed close to the upstream reach breaks, and at one or two transect locations in the middle of the reach, depending on reach length. We located the samples to avoid obvious confounding factors such as bridges and tributary junctions, and to coincide with cross sections in the hydrodynamic model (described below). We sampled in 'run' sections with width and depth generally representative of each reach. At each transect, we sampled three locations spaced across the channel, though only the mid-channel samples are included in this analysis.

Substrate data were collected in July 2004 in water depths ranging from approximately 2 to 10 meters using a boat-mounted underwater digital video system, similar to that developed by Idaho Power Company in their Hells Canyon investigations (Idaho Power Company Staff 2004). Typically, after the boat was maneuvered to the pre-determined sample locations, the video camera was lowered into the water via a gas-powered winch system while the boat was held in position by the driver. The video camera was mounted approximately 1 m above a 25-lb sounding weight; when the sounding weight was resting on the bottom, the camera field of view was approximately 1 m^2. An all-thread rod was mounted to project from the front of the sounding weight, with two golf balls attached to the rod and spaced at 0.3 m apart to provide scale elements in the frame during image capture. When the sounding weight came to rest on the bottom, the winch cable was drawn taught to position the video camera as normal to the channel bed as possible. Once in place, approximately 30 seconds of footage were recorded, with digital still images captured every second.

For sample calibration, we also captured digital images over a similar surface area on four exposed mid-channel bars, where manual pebble counts were also conducted. We endeavored to gather a calibration point on at least one bar within each sampling reach. However, we found few suitable locations within the study reach, as the remnant bar surfaces were typically colonized by perennial grasses such as Reed Canary Grass, precluding both photo and manual sampling.

The captured substrate images were converted via image granulometry software (WipWare Inc 2002) to area-by-weight (photo-sieved) samples, with three replicate images processed for each sample site. The area-by-weight (photo-sieved) samples were then converted to volume-by-weight distributions following Kellerhals and Bray's (1971) voidless cube model, and compared to the manual pebble counts, which were assumed equivalent to volume-by-weight samples (Kellerhals and Bray 1971, Bunte and Abt 2001). Prior to comparison of sampling methods, both distributions were truncated at 8mm. Figure 4 shows an example comparison between raw area-by-weight, converted volume-by-weight, and manual pebble count particle size distributions (PSDs)

Contrary to expectations, the transformation from area-by-weight (photo-sieved) PSDs to volume-by-weight values did not yield PSDs equivalent to the manual pebble counts. We suspect that there is a systematic bias in the photo-sieving routine that causes the transformed photo-sieved PSDs to plot much finer than would be expected. Based on our limited data set, we found that the raw photo-sieved PSDs are approximately similar to the manual pebble count data and, thus, we used the raw photo-sieved PSDs for the current analysis. However, we do not propose this correlation as general evidence of equivalence between photo-sieved area-by-weight PSDs and grid-by-number (pebble count) PSDs. Figure 5 shows the distribution of mid-channel median surface grain sizes across the sampling reaches, and in relation to the channel profile and major tributary junctions.

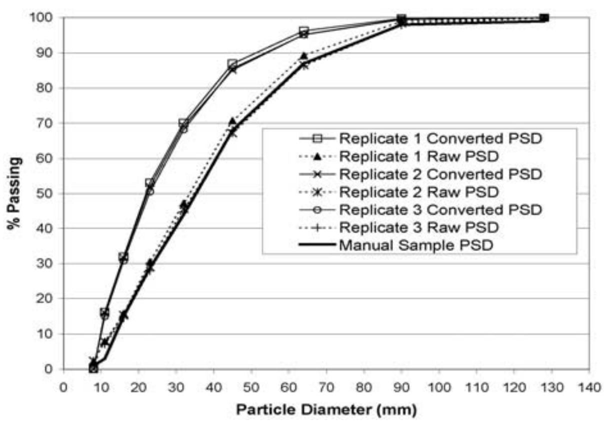

Figure 4 Example comparison between particle size distributions (PSDs) determined from manual pebble count, raw area-by-weight (photo-sieved image), and converted area-by-weight to volume-by-weight.

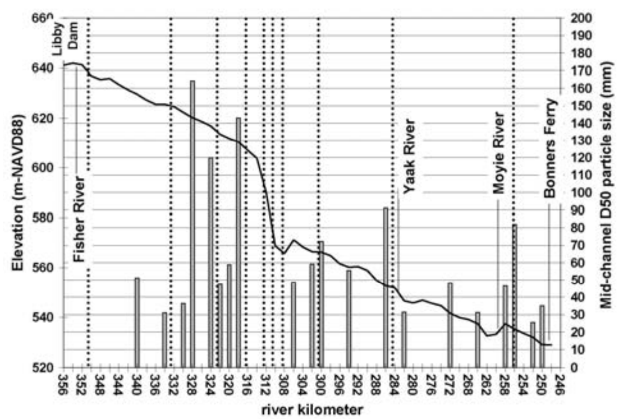

Figure 5 Downstream variation of mid-channel median bed surface grain size (bars) superimposed over the longitudinal profile of the channels, with locations of study reach breaks (dotted lines) and major tributary inputs (solid lines with labels) shown.

IMPACTS OF REGULATION ON BED MOBILITY

We used the 1-dimensional hydrodynamic model Mike 11 developed by the Danish Hydraulic Institute (DHI Water & Environment 2003) to estimate the hydraulic conditions of our sample sites for representative years during the pre-dam and post-dam eras (Burke In preparation). The modeling results are based on cross-sectional data collected by the Idaho District of the USGS during 2003-04 (Barton et al. 2004), and are part of a series of 1-D hydrodynamic models constructed between Libby Dam and Kootenay Lake that we are developing to support the larger assessment of operational losses (Dibrani 2003, Zelch 2003, Benjankar In preparation, Burke In preparation). While it would be preferable to use historic cross-sectional data for modeling the pre-dam conditions, no such data exist for the Kootenai River above Bonners Ferry. Consequently, we use the modern cross-sectional data to model both the pre- and post-dam conditions. Previous coarse-level evaluations of post-dam channel change in the 'canyon' reach (West

Consultants 1998, Dibrani 2003) suggest that this is a valid assumption . The upstream and downstream boundary conditions for the models used in this analysis are derived from extended long-term gage records (the Kootenai River gage below Libby Dam (USGS), and the Kootenay Lake gage at Kuskonook (Water Survey of Canada (WSC)), respectively). The models include lateral inputs for major tributaries and hydrologic gain over the modeled reach, and have been calibrated at several mainstem gage locations between the upstream and downstream boundaries (Burke, in preparation).

We assessed bed mobility by comparing modeled shear stresses to critical values predicted from the Shields (1936) equation. The predicted critical shear stress for each observed median grain size was compared with the local cross-section averaged shear stress predicted from the 1-D hydrodynamic models. Recognizing the uncertainty in selecting a critical Shields parameter (τ^*_{c50}), we used two Shields values (0.03 and 0.06) in our analysis, with 0.03 as a conservative value, and 0.06 as a less conservative value (Buffington and Montgomery 1997). Doing so, we estimated a range of possible mobilities based on these values. For the incipient motion evaluation, we ran 1-D hydrodynamic simulations over the water year (October 1 – September 30) for paired pre-dam and post-dam years having relatively high (1956 and 1996) and moderate (1962 and 1993) values of annual peak flow and mean annual flow. The frequency analyses based on the extended unregulated flow record for the Kootenay River gage at Wardner (WSC, above the reservoir) is summarized in Table 1 for these year pairs.

Table 1 Summary of frequency analysis for year pairs considered in the incipient motion analysis based on the unregulated Kootenay River gage at Wardner, upstream of the reservoir.

Case		Reference Years		Return Interval	
Annual Peak Flow	Mean Annual Flow	Pre-Dam	Post-Dam	Peak Flow Basis	Mean Annual Flow Basis
high	high	1956	1996	1 in 15	1 in 15-20
moderate	moderate	1962	1993	1 in 1.5	1 in 1.5

Although we estimated bed mobility using two critical Shields parameters (0.03 and 0.06), here we present only the results for 0.03 to demonstrate key trends. The results using 0.06 showed similar relative trends between the scenarios, though as expected, indicated less mobility for all cases. The predicted extent of bed mobility for the 1956-1996 high flow-year pair and for the 1962-1993 moderate flow-year pair are shown in Figure 6. The thalweg profile for the reach and major tributary confluences are also shown for reference.

The pre-dam high flow result (1956) shows a regular pattern of mobility distributed over the study reach, with mobility occurring exclusively during the April – July high flow period. The pattern of pre-dam mobility uniformly precedes the cottonwood and willow recruitment period (timing of seed dispersal and recruitment period are indicated on Figure 6) described by the 'riparian recruitment box model' which summarizes the dependency of these trees on flow pattern (Mahoney and Rood 1998, Amlin and Rood 2002). Mobility that directly precedes the timing of seed dispersal should result in fresh recruitment surfaces for the riparian tress. For the post-dam high flow year (1996), significant mobility is also indicated. Examination of this mobility pattern shows that flows are maintained at higher levels throughout the year, though the mobility is limited to fewer sites. Sustained mobility through fall and winter may have the adverse effect of scouring successfully recruited seedlings from the preceding recruitment period. Moreover, the fact that mobility is less evenly distributed over the study reach, but for longer periods, suggests that while the locations with larger grain sizes are not being scoured, the finer grained locations are being scoured more frequently. This is consistent with the observed deficit of finer grained materials in the study reach since regulation commenced (Polzin and Rood 2000).

The moderate flow-year pair indicates 'regular' conditions, and was selected because the peak flow return interval for these years is 1 in 1.5, which many consider to approximate the bankfull or channel-forming flow (Wolman and Miller 1960, Leopold et al. 1964). The extent of bed mobility for this year pair is also shown in Figure 6. For the pre-regulation case, a regular pattern of mobility is apparent and is distributed over the reach, similar in character to the pre-regulation high flow (1956) result discussed above. For the regulated case, limited mobility is indicated, suggesting that the bed materials are mobile less frequently than the pre-regulation case, and less frequently than typical channel-forming flows in unregulated coarse-grained rivers. This result is consistent with field observations that include pervasive growth of perennial vegetation (i.e. primarily grasses) on bar surfaces (Polzin and Rood 2000, Burke In preparation).

Several trends may be inferred from these results. Consistent with our initial hypothesis, the pre-regulation flow regime has the potential to regularly move the contemporary channel bed, while the regulated flow regime is unable to do so. This is demonstrated by the comparison of the results for the moderate flow-year pair, and is consistent with field observations of decreased bed activity. We also found that the regulated flow regime may mobilize sediments in the study reach in high flow years. However, it appears that this mobility may be biased towards finer materials, which may exacerbate the observed deficit of fine sediments in the study reach, and that this mobility may occur during periods that are detrimental to riparian processes native to the basin and region. Finally, these results show that flow magnitudes similar to the pre-regulation channel-forming flow may be required to initiate regular movement of the bed. This is a constraint for restoration planning efforts as the pre-regulation channel-forming flow exceeds current powerhouse and spillway capacity.

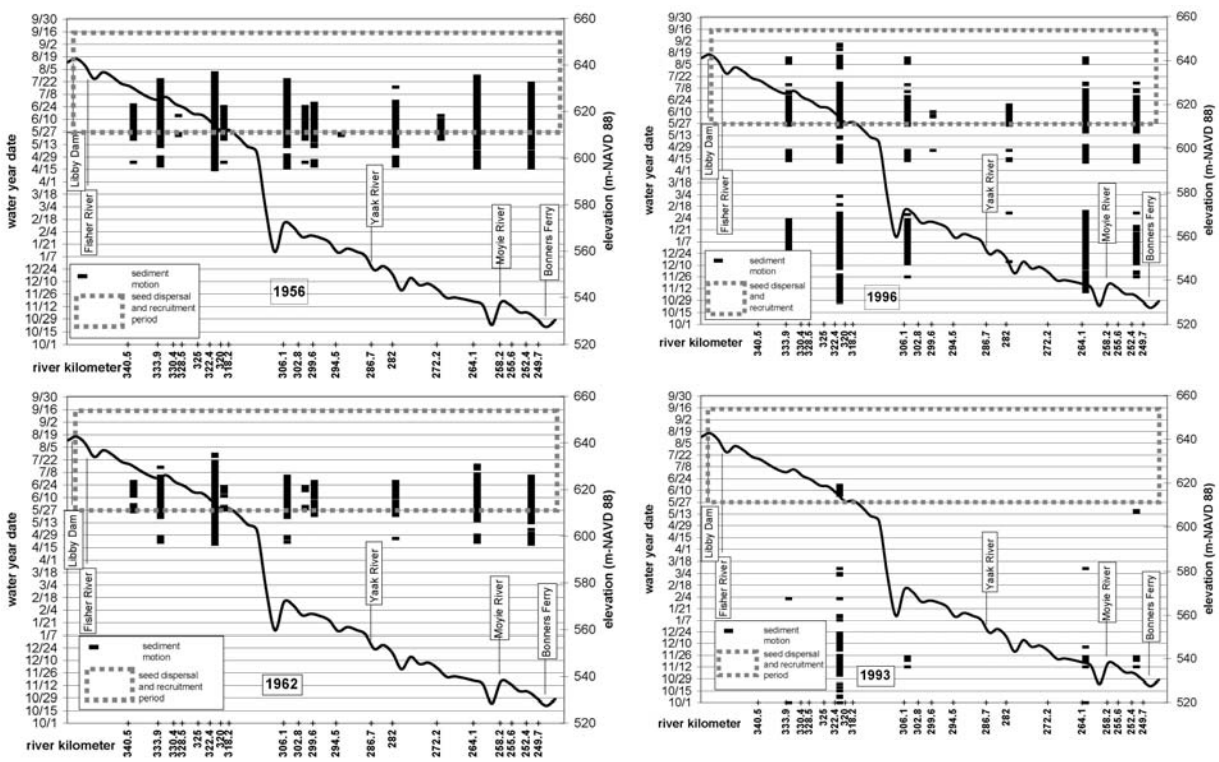

Figure 6 Spatial and temporal extent of bed mobility assuming a critical Shields parameter value of 0.03, in relation to periods of seed dispersal and cottonwood recruitment for pre-dam (1956, upper left) and post-dam (1996, upper right) high flow years, and pre-dam (1962, lower left) and post-dam (1993, lower right) moderate flow years. The dashed box denotes the seed dispersal and recruitment period for riparian trees.

Results using a critical Shields value of 0.06 show similar relative trends in mobility between cases, though less mobility is indicated for all cases. This would suggest that decreased bed activity is even more pronounced as a result of regulation, and correspondingly higher magnitude flows would be required to initiate movement of the bed. As discussed above, the restoration of these high flows is unlikely given current facility constraints.

CONCLUSIONS AND SUMMARY

Libby Dam operations have impacted the potential for bed motion in the study reaches between the dam and Bonners Ferry, Idaho. The stability of the current bed is a limiting factor to many physical and biological processes within the river and its adjacent floodplain. Our analysis suggests that flows with pre-dam recurrence intervals of 1 to 1.5 years would be required to initiate motion of the bed materials in the study reaches. Since flows of this magnitude are not obtainable within current powerhouse discharge and spill constraints, the channel bed will likely remain stable for extended periods, with associated ecosystem impacts. Given this, sediment augmentation downstream of the facility may be required to provide mobile sediment to interact with the channel and current hydrologic regime to lessen the ecological impacts associated with the otherwise stable bed.

We also found that the substrate sampling methods applied in this study were effective for gathering data in relatively deep water. The raw photo-sieved PSDs correlated well with manual pebble count data. However, the photo-based techniques required considerable analysis time in the office, in particular to edit the digitized particle mesh that was generated prior to the actual photo-sieving of each sample.

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