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Application of a hierarchical framework for assessing environmental impacts of dam operation: Changes in streamflow, bed mobility and recruitment of riparian trees in a western North American river

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ABSTRACT

River systems have been altered worldwide by dams and diversions, resulting in a broad array of environmental impacts. The use of a process-based, hierarchical framework for assessing environmental impacts of dams is explored here in terms of a case study of the Kootenai River, western North America. The goal of the case study is to isolate and quantify the relative effects of multiple dams and other river management activities within the study area and to inform potential restoration strategies. In our analysis, first-order impacts describe broad changes in hydrology (determined from local stream gages), second-order impacts quantify resultant changes in channel hydraulics and bed mobility (predicted from a 1D flow model), and third-order impacts describe consequences for recruitment of riparian trees (recruitment box analysis). The study area is a 233 km reach bounded by two dams (Libby and Corra Linn). Different times of dam emplacement (1974 and 1938, respectively) allow separation of their relative impacts. Results show significant changes in 1) the timing, magnitude, frequency, duration and rate of change of flows, 2) the spatial and temporal patterns of daily stage fluctuation, unit stream power, shear stress, and bed mobility, and 3) the potential for cottonwood recruitment (*Populus* spp.). We find that Libby Dam is responsible for the majority of first and second-order impacts, but that both dams diminish cottonwood recruitment; operation of Corra Linn adversely affects recruitment in the lower portion of the study reach by increasing stage recession rates during the seedling establishment period, while operation of Libby Dam affects recruitment in the middle and upper portions of the study reach by changing the timing, magnitude, and duration of flow. We also find that recent experimental flow releases initiated in the 1990s to stimulate recovery of endangered native fish may have fortuitous positive effects on cottonwood recruitment potential in the lower portion of the river. This case study demonstrates how a process-based, hierarchical framework can be used for quantifying environmental impacts of dam operation over space and time, and provides an approach for evaluating alternative management strategies.

1. Introduction

The societal benefits of the use of our rivers are profound, including irrigation, transportation, flood control, power generation and recreation. As a result of our sustained development of these resources, river systems have been altered significantly worldwide (Naiman et al., 2005), with nearly 60% of major river basins fragmented by large dams (Revenga et al., 2000). In the continental United States, 75,000 dams contain storage volume nearly equalling one year's mean runoff (Graf, 1999). Of greater significance, however, is the impact that river management has had on ecological resources (Naiman et al., 2005).

Dams and reservoirs impact the environment through their presence in the landscape, altering basin connectivity and modifying thermal, hydrologic and sediment regimes, with the magnitude of change unique to each facility (Ligon et al., 1995; Poff and Hart, 2002; Grant et al., 2003). The way in which the facility is operated can also impact the environment (Church, 1995; Richter et al., 1996; Poff et al., 1997; Naiman et al., 2005; Jager and Smith, 2008). A broad array of operational impacts may occur depending on the purpose of the facility (e.g., consumptive storage, flood control, hydropower), the architecture of the system (e.g., number, size, and sequence of dams, reservoirs, and diversions), and the physiographic setting (climate, geology, topography), but in general

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facility operation causes a cascade of effects on hydrology, hydraulics, river and floodplain morphology, and riverine ecology, with potentially complex biophysical feedback loops (e.g., Naiman et al., 2000; Rood et al., 2005).

A process-based hierarchy is an effective means for representing this succession of impacts, and provides a 'roadmap' for exploring and assessing the processes linking successive levels of impact. Jorde et al. (2008) proposed a hierarchy for considering operational impacts on floodplain ecosystems (Fig. 1), adapted from a framework originally proposed by Petts (1984). In this hierarchy, first-order impacts are changes to the primary physical drivers of the fluvial system: hydrology, water quality and sediment supply (Williams and Wolman, 1984; Richter et al., 1996; Poff et al., 1997; Naiman et al., 2000; Grant et al., 2003). Changes in hydrology and sediment supply lead to second-order impacts of altered hydraulics, sediment transport, and channel and floodplain morphology (e.g., Gilbert, 1917; Williams and Wolman, 1984; Church, 1995; Webb et al., 1999; Grant et al., 2003). Third-order impacts represent the combined influence of first- and second-order impacts on biological functions through direct and indirect linkages (Ligon et al., 1995; Jorde and Bratrich, 1998; Naiman et al., 2000; Rood et al., 2005). Fourth-order impacts describe feedback between biological responses and physical processes (Naiman et al., 2000; Rood et al., 2005). This cascade of impacts often results in compromised ecosystem integrity (Ward and Stanford, 1983; Richter et al., 1996; Poff et al., 1997; Nilsson and Berggren, 2000; Tockner and Stanford, 2002; Naiman et al., 2005; Jorde et al., 2008). In particular, prior studies have shown that hydrology is a fundamental driver of riverine ecosystems and that ecosystem function may depend on the full suite of naturally occurring flows (Poff et al., 1997; Naiman et al., 2000). Hence, river management is frequently in conflict with ecosystem function, the preservation of which may depend on management compromises and plasticity of riverine organisms to environmental changes imposed by management.

In this study, we investigate the hierarchical impacts of dam operation on hydrology, channel hydraulics, bed mobility, and recruitment of riparian trees in a western North American river. We focus on the recruitment of cottonwoods (*Populus* spp.) because they are native to the study area and because of their general importance as structural elements in riparian areas of western North America (Braatne et al., 1996; Rood et al., 2005). Successful establishment of cottonwood seedlings is intimately linked to channel morphology, sediment transport, and the timing, magnitude, and duration of streamflow, all of which are represented by the 'cottonwood recruitment box model' (Braatne et al., 1996; Mahoney and Rood, 1998; Amlin and Rood, 2002), discussed further in Section 3.3. Although developed for cottonwoods, this conceptual model has also been applied to other riparian species (Dixon and Turner, 2006). Alternative approaches for quantifying the potential recruitment and distribution of riparian vegetation include population models (Lytle and Merritt, 2004), stochastic models (Camporeale and Ridolfi, 2006) and analyses of recruitment bottlenecks (Stella et al., 2006).

We use the Kootenai River, western North America, as a case study for assessing hierarchical impacts of dam operations on riverine ecosystems. This site was selected because of an extensive data base available for conducting the analysis, and because it is the focus of a larger investigation of ecosystem losses to historic Native American lands along the lower Kootenai River due to operation of Libby Dam (Kootenai Tribe of Idaho, 2006). Furthermore, we focus on quantifying the relative impacts of multiple dams and other river management activities within the study area to isolate the specific effects of Libby Dam and to better inform potential restoration strategies. This case study is intended to demonstrate the value of using a process-based, hierarchical framework for quantifying ecosystem losses that may result from dam operations and for evaluating alternative management strategies.

2. Study area

The Kootenai River basin has a total drainage area of 41,910 km^2 and comprises parts of British Columbia, Montana, and Idaho (70%, 23% and 7% of basin area respectively; Fig. 2). From the headwaters, the Kootenai River drops 3090 m to where it enters Kootenay Lake, and is the second largest Columbia River tributary in terms of runoff volume. The study area is a 233 km reach of the river between Libby Dam and Kootenay Lake, referred to as the lower Kootenai River, and is divided into three geomorphic subreaches (Snyder and Minshall, 1996): a canyon reach, a braided reach, and a meandering reach (Fig. 2). The canyon reach is 100 km long and is characterized by alternate confined and semi-confined sections, with pool-riffle and plane-bed channel morphologies (Montgomery and Buffington, 1997). Bed surface material in the canyon reach ranges from gravel to small boulders. The braided reach is relatively short (11 km), with a wider floodplain and a complex of secondary channels that are seasonally active. Bed surface materials in the braided reach are gravels and cobbles. The meandering reach occurs where the Kootenai River enters the glaciated, north–south trending Purcell Trench. In this 122 km reach, the channel meanders across an extensive, 5 km wide floodplain constructed primarily of lacustrine deposits accreted during periods when the west arm of Kootenay Lake was dammed by glacial ice (Kootenai Tribe of Idaho and Montana Fish Wildlife & Parks, 2004). The bed and banks in this reach are constructed of fine-grained silts and sands, and the channel is heavily influenced by the hydraulic backwater of Kootenay Lake.

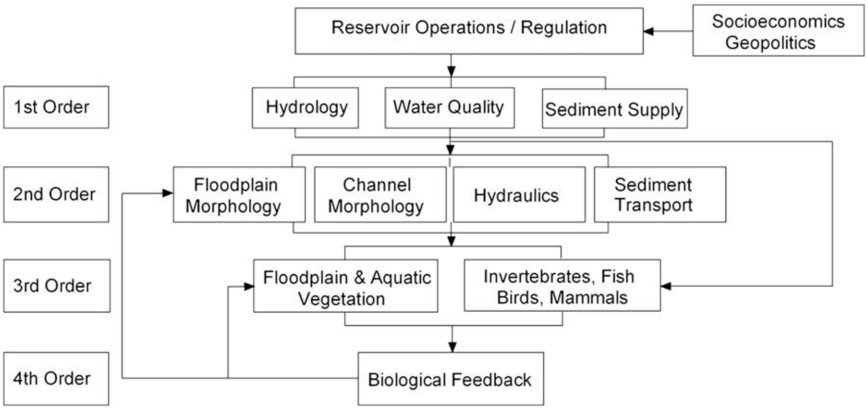

Fig. 1. Hierarchy of physical and biological impacts caused by dam operation. Modified from Petts (1984) and Jorde et al. (2008).

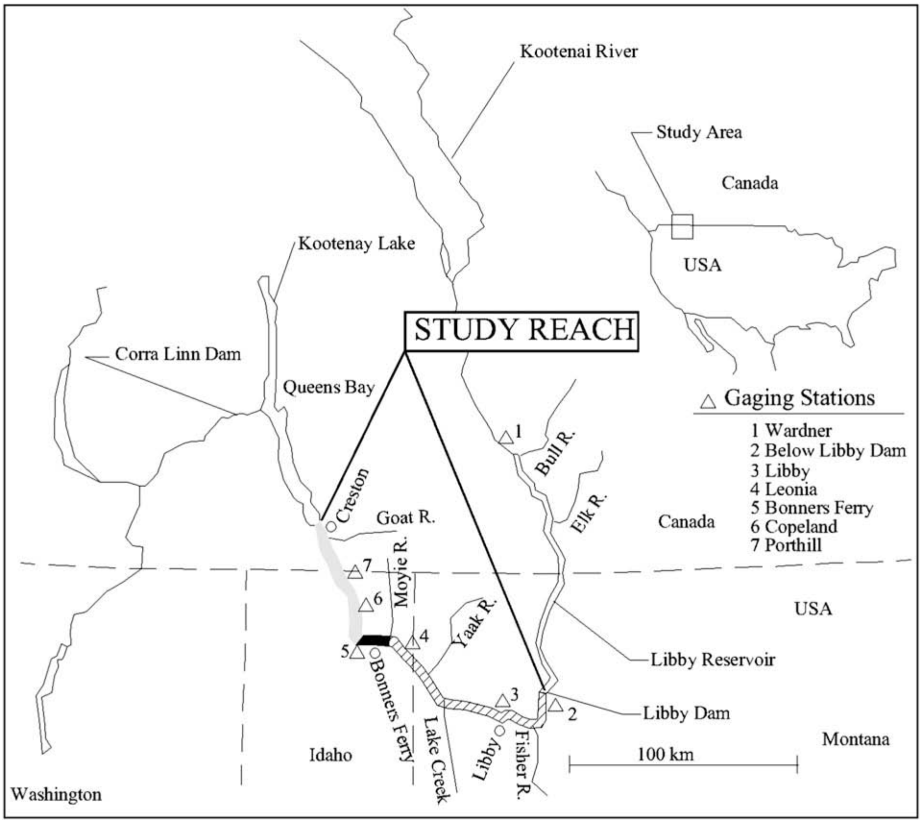

Fig. 2. Location of the study site, dams, geomorphic subreaches (canyon, hatched; braided, black; meandering, gray) and gaging stations. Modified from Jorde et al. (2008).

2.1. River management

The water resources of the lower Kootenai River have been actively managed since the late 1800s (Northcote, 1973). Prior to European settlement, the river constructed natural levees in unconfined, floodplain sections of the river when flood waters overtopped the banks and deposited sediment on the floodplain. These natural levees were improved following European settlement to reclaim the Kootenai bottomlands for agricultural use (Kootenai Tribe of Idaho and Montana Fish Wildlife & Parks, 2004). Estimates of the progress of levee construction, drainage installation and floodplain conversion for dryland agriculture suggest that 50% of the floodplain (21,000 hectares) was behind dikes by 1939 (Tetratech, 2004).

In the 1930s, Corra Linn Dam was constructed at the outlet of Kootenay Lake to generate hydropower and control floods. Lake levels have been managed since 1939, with higher stages maintained during low-flow periods (September–February) to enhance energy production, and lower stages maintained during the high-flow spring and summer months to create flood storage. Enlargement of the lake outlet in conjunction with the construction of Corra Linn Dam allows Kootenay Lake levels to be lowered relative to historic levels, which limits inundation of the Kootenai floodplain adjacent to the meandering reach.

Flood control activities continued during the 1940s and 1950s through additional levee construction, and extensive maintenance and repair of existing levee systems (U. S. Army Corps of Engineers, 1951, 1960), with these activities largely complete prior to construction of Libby Dam. Libby Dam was completed in 1974 and is operated to meet power generation and flood control objectives, and as a headwaters storage facility for the Federal Columbia River Power System. The 130 m tall structure is located 357 river kilometers above the river mouth, and creates a 145 km long reservoir that straddles the Canada–USA border, impounding the upper 23,200 km^2 of the basin (Fig. 2). Although Libby Dam reduces peak flow events, there is no inter-annual storage, resulting in mean annual flows similar to the pre-dam period. Stored water is not withdrawn from Libby Reservoir for other uses (e.g., irrigation, water supply).

2.2. Basin hydrology

The natural flow regime for the Kootenai River was snowmelt-dominated, with a sustained peak in late spring, followed by a gradual recession to baseflow by September, and low winter flows. Historically, spring runoff occurred between April and June, with discharge increasing an order of magnitude over winter baseflow (Fig. 3). Emplacement and operation of Libby Dam have evened out the historic hydrograph, reducing peak spring events and increasing fall and winter baseflows. Adverse ecosystem impacts attributed to the operation of Libby Dam include: 1) limited recruitment of native fish, such as white sturgeon (*Acipenser transmontanus*) (Paragamian et al., 2001; Anders et al., 2002) and burbot (*Lota lota*) (Paragamian et al., 2000), 2) disruption in recruitment of black cottonwood (*Populus trichocarpa*) (Polzin and Rood, 2000), and 3) altered nutrient dynamics (Snyder and Minshall, 1996) and benthic ecology (Hauer and Stanford, 1997).

Kootenay Lake also has a strong influence on basin hydrology. It is a naturally formed water body that has controlled downstream water levels for the lower Kootenai River since glaciation. The backwater influence of Kootenai Lake extends south of the international boundary past Bonners Ferry, reaching approximately 126 km upstream (Fig. 2). Historically, lake levels mirrored the snowmelt-driven Kootenai River hydrograph, but since the 1930s have been controlled by Corra Linn Dam.

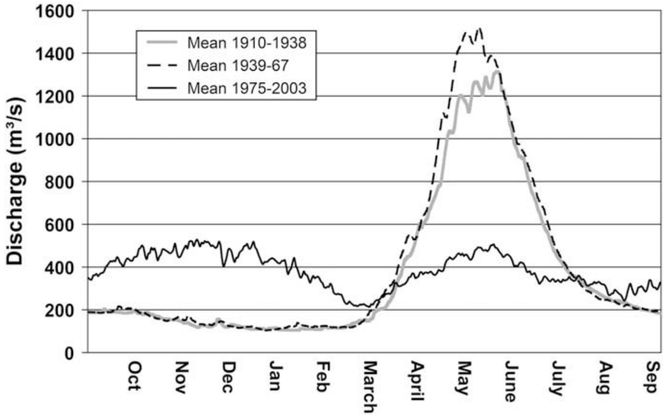

Fig. 3. Flow record for USGS gage # 12305000, Kootenai River at Leonia, adjacent to Idaho–Montana state boundary (Fig. 2), for historic (1910–1938), pre-Libby Dam (1939–1967) and post-Libby Dam (1975–2003) periods.

3. Methods

We use a hierarchical approach for quantifying the spatial and temporal impacts of the dams on the study reach. First-order impacts describe broad changes in hydrology (timing, magnitude, frequency, duration and rate of change of streamflow as determined from gages within the study area), second-order impacts quantify resultant changes in channel hydraulics and bed mobility (predicted from a 1D flow model), and third-order impacts describe consequences for recruitment of cottonwoods (recruitment box analysis). Methods for each level of the hierarchy are discussed in detail below. Three time periods are examined to isolate the effects of Libby Dam from other river management activities: historic (1910–1938, prior to operation of Corra Linn Dam), pre-Libby Dam (1939–1967, including operational impacts of Corra Linn Dam and other reclamation activities (e.g., levees, dikes, floodplain drainage)), and post-Libby Dam (1975–2003, including operational impacts of Libby Dam and all other river management activities). Topographic cross sections were obtained for each time period through a combination of contemporary surveys and data mining (see Burke (2006) for further detail), allowing operational impacts to be examined in both a spatially and temporally distributed manner. Comparison between historic and post-Libby Dam time periods quantifies the total perturbation of the system, incorporating the operations of both the Corra Linn and Libby facilities, and the effects of other river management activities such as levee construction. Furthermore, because reclamation activities were finalized by the end of the pre-Libby Dam era, comparison between the pre-Libby Dam and post-Libby Dam periods isolates the impacts of Libby Dam.

3.1. *Assessment of first-order impacts*

In our analysis, first-order impacts describe broad changes in hydrology resulting from dam operation. Here, we focus on changes in the hydrologic regime caused by Libby Dam. To assess this particular impact, time series of daily mean discharge for 7 mainstem gages were evaluated using the Indicators of Hydrologic Alterations (IHA) (Richter et al., 1996, 1998) and associated software (Nature Conservancy, 2007). Comparison of pre- and post-Libby Dam periods allows evaluation of the dam's effects on hydrology (Richter et al., 1996). Furthermore, we conduct the analysis for multiple gages throughout the drainage basin, allowing finer-scale resolution of the spatial distribution of impacts (Richter et al., 1998). The Wardner gage upstream of Libby Reservoir was used as an unregulated control in the analysis to account for any non-stationarity of climatic conditions or other confounding influences during the period of interest, with the other 6 gages located downstream of Libby Dam (Fig. 2).

3.2. *Assessment of second-order impacts*

In this study, second-order impacts describe changes in channel hydraulics and bed mobility resulting from first-order changes in hydrology. Channel hydraulics and bed mobility were predicted using a one-dimensional hydrodynamic flow model (MIKE 11; DHI Water & Environment, 2003). Individual models were developed and calibrated for each time period (historic, pre-Libby Dam and post-Libby Dam) using representative discharge and cross-sectional data (see Burke (2006) for further detail). This approach allows explicit simulation of the spatiotemporal flow characteristics for each time period.

The spatial and temporal variability of seven parameters were assessed from the hydrodynamic models: maximum flow depth, wetted width, daily stage fluctuation, velocity, bed shear stress, unit stream power and bed mobility. In general, these parameters provide insight into aquatic habitat conditions of the river, the interaction of the river with the riparian zone, and the ability of the river to alter its bed and banks. Bed mobility is defined as the applied shear stress for a given flow (τ) relative to the critical stress needed to mobilize the local median grain size ($\tau_{c50} = \tau^*(\rho_s - \rho)gD_{50}$, where τ^* is the Shields parameter (set equal to 0.03), ρ and ρ_s are fluid and sediment densities, respectively, g is gravitational acceleration, and D_{50} is median surface grain size). Underwater videography was used to determine bed material size distributions throughout the study area (Burke et al., 2006).

Second-order impacts were determined by comparing the above parameters between similar water years within each time period. Selected water years represented a range of climatic conditions (wet, average and dry). Two steps were taken to assess changes in the hydraulic and bed mobility parameters. First, a plot of the spatial and temporal distribution of each parameter was developed for representative years of wet, average and dry conditions. Fig. 4 shows an example for comparable average water years during the pre- and post-Libby Dam periods. The temporal distribution is represented by the vertical axis, starting with the first day of the water year at the origin. The spatial distribution is shown along the horizontal axis in terms of distance downstream from Libby Dam. For each combination of time and space, a unique parameter value (shaded pixel) is plotted, with darker shading corresponding to higher magnitude values. These plots allow rapid visual assessment of differences between time periods, or between current conditions and future management scenarios.

Next, the alteration of a given parameter between two time periods was calculated with respect to space and time of year ($A_{X,T,i,j}$)

$$A_{X,T,i,j} = \left|P_{X,T,i} - P_{X,T,j}\right| \tag{1}$$

where P is the value of a particular instream parameter at a given location (X, river kilometer) and time of year (T, calendar day) for a given pair of years (i,j) between two time periods (e.g., historical vs. post-Libby Dam periods). The change in a given parameter was then summed over the study reach and water year (all X and T). This was done for each year pair (i,j) between time periods (e.g., historical vs. post-Libby Dam), with year pairs representing similar climatic conditions (wet, average, dry). Finally, mean values of percent alteration were determined for each parameter across year pairs and averaged to determine an ensemble index of alteration (Section 4.1).

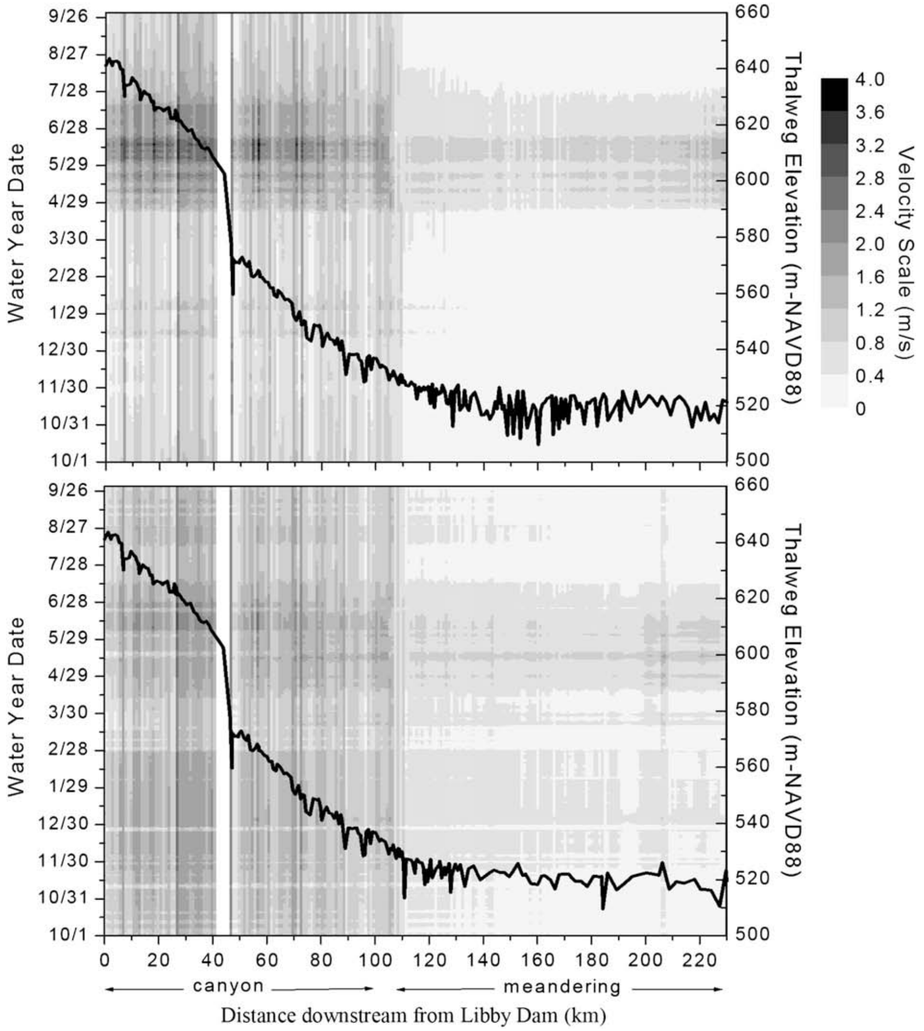

Fig. 4. Spatial and temporal distribution of average velocity for two comparable "average" water years during the a) pre- and b) post-Libby Dam periods (1953 and 1997, respectively). For each combination of time (y-axis) and space (x-axis), the simulated value for average velocity is denoted by a shaded pixel, keyed to values on the right-hand side of the figure. The heavy black line is the longitudinal profile of the thalweg bed elevation.

3.3. *Assessment of third-order impacts*

Third-order impacts describe ecological response to changes in the first- and second-order physical parameters. Here, we examine ecological response in terms of changes in the recruitment potential of black cottonwoods (*Populus trichocarpa*). Limited recruitment of these trees in the lower Kootenai River since the closure of Libby Dam has been primarily attributed to the limitation of upstream sediment supply, selective removal of finer sediments from potential recruitment sites, and modifications of the downstream hydrologic regime (Polzin and Rood, 2000; Jamieson and Braatne, 2001; Burke et al., 2006). Our analysis considers the effects of flow regulation on stage recession patterns during the post-flood seedling establishment period, in a spatially distributed manner through the study reach.

The requirements for successful seedling recruitment can be described by the 'cottonwood recruitment box model' (Braatne et al., 1996; Mahoney and Rood, 1998; Amlin and Rood, 2002). Cottonwood recruitment requires a snowmelt dominated or similar hydrograph, with a large late spring peak or 'spring freshette' to mobilize and redistribute sediments (providing barren germination sites), followed by gradual recession to baseflow during and following the early summer seed release period. The gradual rate of stage recession following the annual snowmelt peak allows newly established seedling roots to stay in contact with adequate soil moisture as they elongate (Braatne et al., 1996, 2007; Mahoney and Rood, 1998). Laboratory studies show that optimal rates for water table decline are approximately 2.5 cm/day. Of equal importance are sustained low flows following the recruitment period to prevent mortality by fluvial scour (Mahoney and Rood, 1998; Burke et al., 2006; Braatne et al., 2007). Braatne et al. (2007) further suggest that in some cases, recruitment of seedlings may lag peak flow events by several years because of unfavorable flows during seed dispersal and germination. In such cases, the barren recruitment sites that result from the high-flow year may be utilized in subsequent, relatively lower flow years when favorable discharge characteristics coincide with the seed release period. For this study, the period of seed release and distribution is considered to be May 20 to July 15 annually.

In their evaluations of stage decline rates on other rivers, Rood and Mahoney (2000) and Braatne et al. (2007) use a convention where a 3-day moving average of daily stage decline from 0 to 5 cm/day is considered favorable for seedling recruitment, while rates between 5 and 10 cm/day are considered stressful, and other rates are considered lethal. To accommodate the natural variability of stage decline, Braatne et al. (2007) further use the concept of a 'mortality coefficient', which is a weighting convention that allows a certain proportion of 'lethal' days to occur during the stage recession period that stress the plant, but do not kill it; the idea is that mortality requires a sustained period, or percentage, of ‘lethal’ days. The mortality coefficient (M) is used in our analysis and is defined as

$$M = \frac{(\%\text{lethal} \times 3) + (\%\text{stressful} \times 1) + (\%\text{favorable} \times 0)}{3} \qquad (2)$$

where %lethal, %stressful, and %favourable are the percent of days during the period of consideration whose moving 3-day average rate of stage decline is considered lethal, stressful, or favorable, respectively. Stage changes that are considered favorable are assigned a weight of 0 in the mortality coefficient calculation and, thus, drop out of the equation. Braatne et al. (2007) consider M values between 20 and 30 marginal, and values greater than 30 unfavorable.

Lastly, Mahoney and Rood (1998) suggest that naturally recruited cottonwoods most frequently occur at elevations between 0.5 m and 1.5 m above late summer baseflow based on observations of seedling establishment along several streams. They cite additional studies on large rivers (e.g., the Missouri) which found that seedlings established at elevations up to 2.6 m above baseflow levels. This elevation window is considered to be the potential ‘recruitment band’ (requisite elevation) in the recruitment box model. For a given year, the correct flow attributes may converge over a subsection of this band, resulting in a unique pattern of seedling establishment (specific elevation band) during those years where recruitment occurs. Subsequent studies of the Kootenai River indicate that in unregulated sites, cottonwood seedlings establish between 1 and 3.8 m above baseflow stage, with the greatest seedling densities occurring between 2 and 3.8 m (Polzin and Rood, 2000; Jamieson and Braatne, 2001). The size of the recruitment band likely scales with river size, such that large snowmelt rivers like the Kootenai have characteristically larger ranges of stage decline following floods (Polzin and Rood, 2000). Based on the above studies we use a recruitment band of 0.5–4 m above the September 15 stage (typical start of baseflow) in our analysis. Table 1 summarizes the ensemble criteria used in our evaluation of cottonwood recruitment potential. This combination of processes was numerically simulated, combining hydrodynamic model results with the criteria described herein to estimate cottonwood recruitment potential for the different time periods examined.

4. Results

4.1. First-order impacts – hydrologic alteration

Operation of Libby Dam has significantly modified the flow regime of the Kootenai River (Fig. 5). While flows are essentially unchanged at the Wardner gage above the reservoir (unregulated control site), the flow pattern at the Libby Dam gage is reversed from the pre-dam era. Significantly greater median monthly flows occur during the winter months (increases of 400–500 m^3/s), which were the typical low-flow period during the pre-dam era, while the annual snowmelt peak has been nearly eliminated (reductions in median monthly flows up to 900 m^3/s) (Fig. 5).

Table 1
Criteria used in evaluation of riparian recruitment potential

Description	Criteria
Annual peak flow	Must occur before or during the seed dispersal period (May 20–July 15)
Recruitment band	0.5–4.0 m above September 15 stage (typical start of baseflow)
Daily stage decline rates (moving 3-day average)	0–5 cm/day – favorable 5–10 cm/day – stressful Other rates – lethal
Mortality coefficient	$M < 20$ – favorable $20 < M < 30$ – marginal $M > 30$ – unfavorable

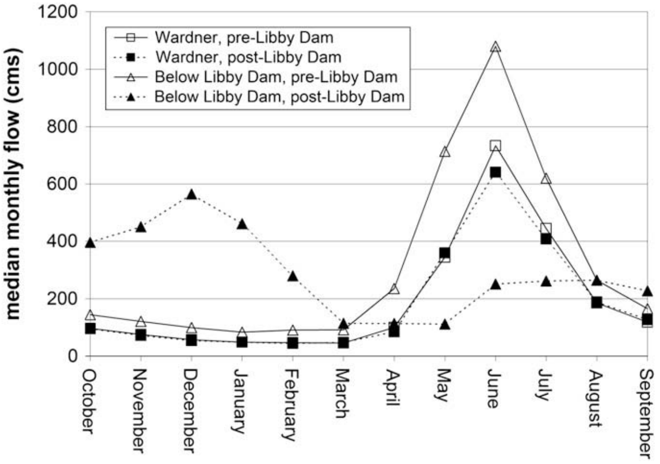

Fig. 5. Median monthly flows for pre- and post-Libby Dam periods above the dam (Water Survey of Canada gage 08NG005, Kootenay River at Wardner) and below it (USGS gage 12301933, Kootenai River below Libby Dam near Libby).

A set of example results from the IHA analysis shows significant changes in the median monthly flows at stream gages downstream of Libby Dam (Fig. 6). Comparable changes are observed at each gage, and there is little downstream attenuation of dam-induced alterations with successive tributary inputs. The largest changes to the median monthly flows occur during the high-flow months of May–July (decreases range from 360 to 900 m^3/s) and the low-flow months of November–January (increases range from 330 to 470 m^3/s). The median annual flow and the median flows for the transitional months of August, September and March are least altered. This pattern is indicative of an inverted annual hydrograph (Fig. 5) and is consistent with the facility’s dual objectives of flood control and hydropower generation, whereby water is stored during high-flow periods for release during traditionally lower flow periods. In contrast to the above results, the unregulated Wardner gage shows essentially no change between the pre- and post-Libby Dam periods, suggesting that any non-stationarity in the discharge record (e.g., climate change) is minimal.

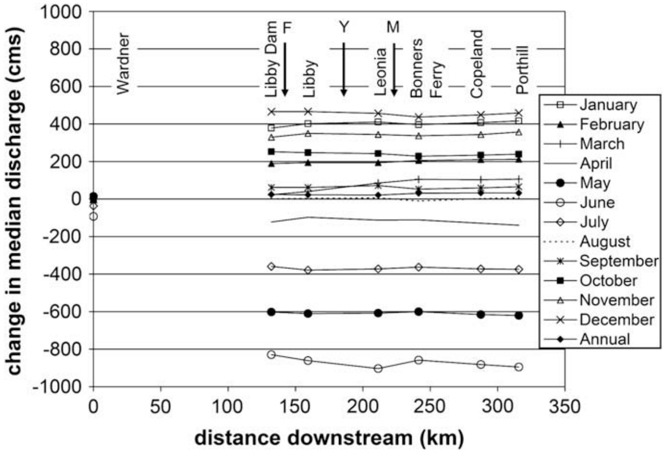

Fig. 6. Change in median monthly flows and median annual flow for 7 mainstem Kootenai River gaging stations between pre- and post-Libby Dam periods (1939–1967 and 1975–2003, respectively). The approximate locations of three major tributaries (F-Fisher River, Y-Yaak River, M-Moyie River) are indicated by arrows.

For this study, a 15-parameter subset of the IHA output was selected to simplify the analysis. The selected parameters represent the 5 core parameter groups reported by the IHA method, but eliminate redundant parameters while still representing the primary characteristics of the pre- and post-Libby Dam hydrology. Results of the IHA analysis were aggregated using a pie chart technique (Fig. 7) similar to that used by Andreasen et al. (2001). In this application, each parameter is given equal weight (i.e., equally sized pie pieces) and the degree of alteration is represented by increasing distance from the gray dashed line (reference condition of zero alteration). Thus, smaller pie pieces correspond with greater change; alterations >100% are shown as blank pie pieces. Note that both increases and decreases relative to pre-disturbance values are considered 'alteration' and thus both cause the size of the respective pie pieces to shrink. The relative sizes of the pie pieces also provide a representation of the uniformity of alteration between parameters. The two parameters showing the largest change were the winter mean daily flow (increased minimum flows during the winter low-flow period) and the high pulse count (number of flows exceeding the 75th percentile of the pre-disturbance flow distribution). The latter reflects increased irregularity of the hydrograph over daily and weekly time scales (seen in Fig. 3 and discussed further below).

4.2. *Second-order impacts – instream parameters (channel hydraulics and bed mobility)*

The spatial and temporal distribution of second-order impacts (change in channel hydraulics and bed mobility) mirror the first-order impacts – reduced flow magnitudes during the snowmelt period (April–June), increased flow magnitudes during the base-flow fall and winter periods, and increased irregularity of flow compared to the historical flow regime (Fig. 8). The high-flow peaks which previously produced the greatest values of velocity, shear stress and stream power are captured in the Libby Reservoir for release during low-flow periods, leveling out these parameters across the year, compared to both the historic and pre-Libby Dam periods (Fig. 8j–r). As such, relatively fewer locations experience bed mobility in the post-Libby Dam period (Fig. 8s–u), however bed mobility is indicated over a greater period of the year at a subset of these locations. This pattern supports observations of selective sediment withdrawal in the study reach (Polzin and Rood, 2000). Results also show that stage fluctuations increase in the post-Libby Dam period due to hydropower generation (Fig. 8g–i), where operational strategies may include increased releases during the business week, reduced releases on the weekend, and daily load following practices. However, channel geometry (maximum depth and wetted width) shows little change, other than reduced peak values in the post-Libby Dam period due to regulation of the annual snowmelt peak (Fig. 8a–f).

Second-order impacts were aggregated using pie charts that respectively describe the total alteration of the study reach (Fig. 9a; historic vs. post-Libby Dam periods) and that due solely to Libby Dam (Fig. 9b; pre- vs. post-Libby Dam periods). An ensemble score for each case was determined by summing the scores for all pie pieces to yield a total mean percent alteration (recall that each pie piece has equal weight). In contrast, the ratio of the largest to smallest pieces provides a measure of the uniformity of alteration, referred to as 'deviation from circularity'. The results are nearly identical for the two cases, suggesting that the effects of Libby Dam dominate this section of the river (91% of the total change can be attributed to Libby Dam). For both cases, changes in the spatial and temporal patterns of stage fluctuation and stream power were the two greatest changes (Fig. 9, alterations in excess of 100%). These are followed by changes in shear stress and bed mobility. Distributions of depth and wetted width have been altered the least of the seven parameters. These alterations are consistent with the dual facility objectives of flood control and hydropower generation.

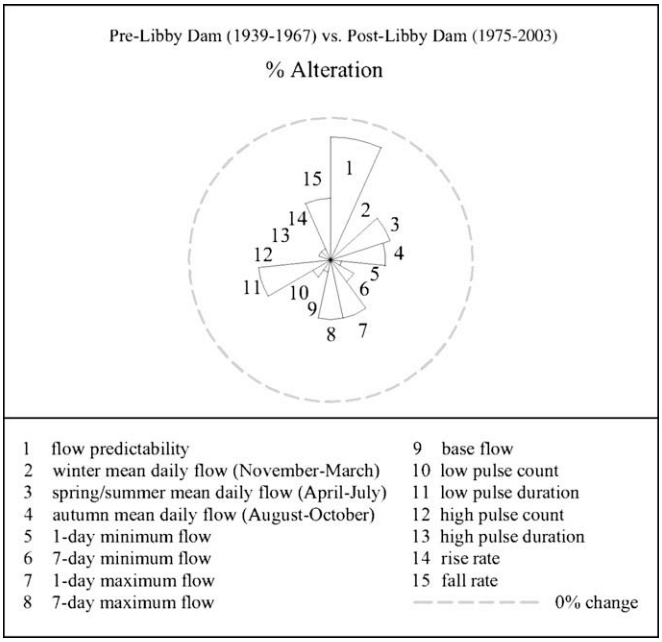

Fig. 7. Pie chart of hydrologic alteration scores for a 15-parameter subset of the IHA output for comparison of pre- vs. post-Libby Dam periods. Distance from the gray line indicates degree of alteration. A 'pulse' refers to an event that exceeds the high-flow threshold or falls below the low-flow threshold, where the thresholds are respectively defined as the 75th and 25th percentiles of the pre-disturbance flow distribution, with pre-disturbance conditions based on the hydrologic record of the pre-Libby Dam period. Pulse 'count' refers to the number of these events typically occurring each year. Pulse 'duration' refers to the typical length (time) of these events.

4.3. *Third-order impacts – cottonwood recruitment potential*

The spatial and temporal distribution of cottonwood recruitment potential varied considerably among dry, average and wet conditions (Fig. 10). These plots map the time period per river kilometer during which appropriate stage elevation and stage decline rate converge within the period of seed release and dispersal. The black shading denotes dates and locations where the subsequent stage recession curve exhibits favorable conditions for seedling establishment, while the gray shading indicates marginal recruitment conditions, and no shading indicates conditions unfavorable for recruitment. Although the availability of nursery sites and the implications of post-establishment scouring events were not explicitly evaluated, several trends were identified from this analysis. Results for both the historic and pre-Libby Dam periods indicate that recruitment potential is limited during wet years, and increases significantly for dry years. It appears that the timing, volume and magnitude of the wet year peaks delayed convergence of appropriate stage decline rates and elevations until after the period of seed distribution ceased (Fig. 10a–c). In average years, recruitment opportunity increases for the historic period relative to wet years in the upstream portion of the reach (Fig. 10d).

The low-flow years appear to have the greatest potential for seedling establishment during the historic and pre-Libby Dam periods (Fig. 10g–h). Given lower peak flows and reduced peak volume, river stages persist within the recruitment band for much of the seed distribution period, and decline slowly to late summer levels. While the stage decline patterns suggest recruitment in the low-flow years, these lower discharges may not be sufficient to create widespread nursery locations through scour and deposition

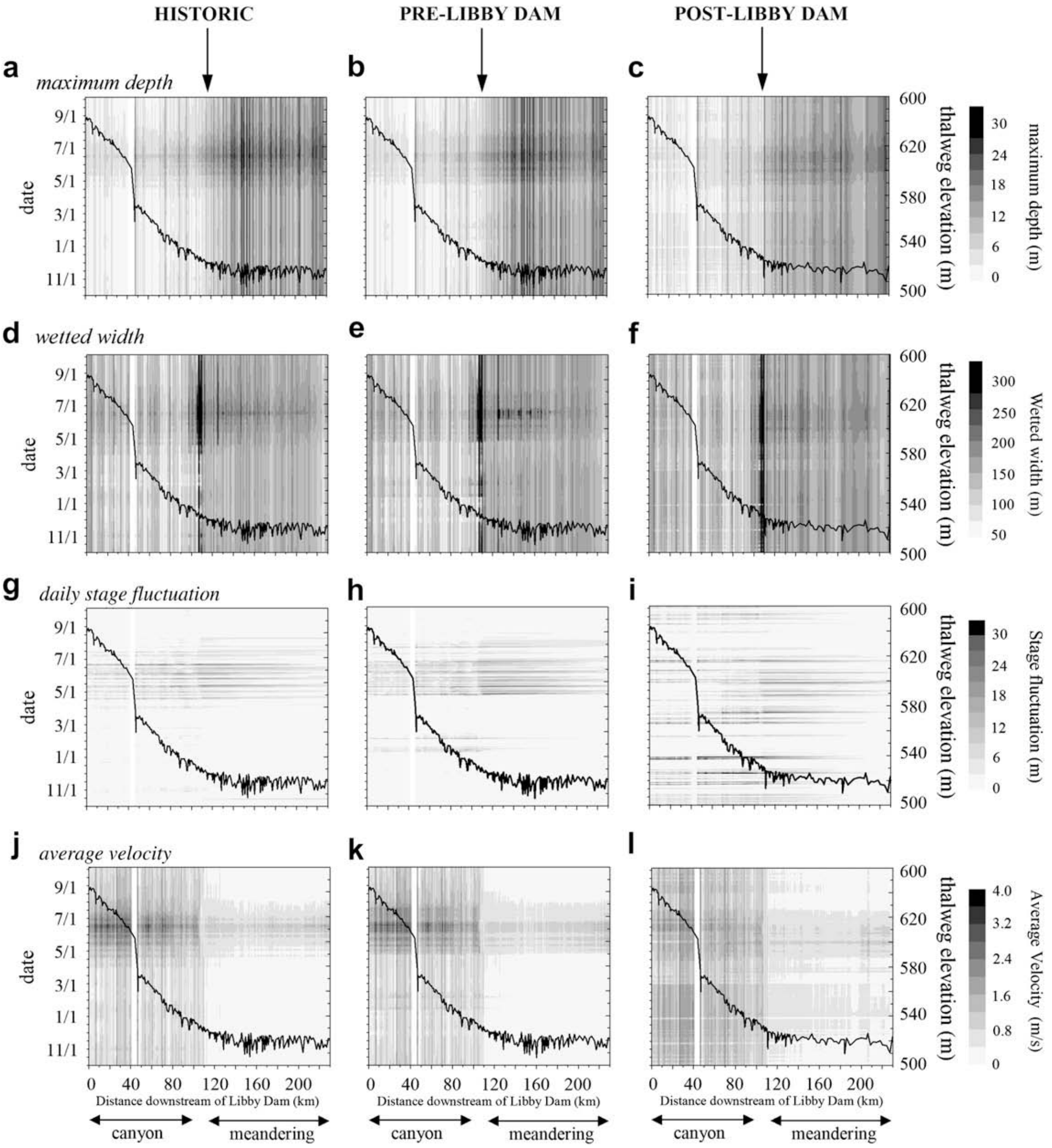

Fig. 8. Spatial and temporal distribution of channel hydraulics and bed mobility for comparable "average" water years during historic (1917), pre-Libby Dam (1966), and post-Libby Dam (1978) periods. The heavy black line is the longitudinal profile of the thalweg bed elevation.

along the channel margins (Burke et al., 2006). If so, cottonwood recruitment historically may have been a multi-year process, whereby high-flow years were necessary to create nursery sites through erosion and deposition, and subsequent low-flow years were required to fulfill the discharge requirements for seedling establishment (Braatne et al., 2007). Alternatively, an intermediate condition, characterized by the intersection of high enough peak flow to create nursery sites, yet low enough flow volume to satisfy establishment requirements within the seed release period, may have been most effective. This concept is analogous to that of the dominant or bankfull discharge in fluvial geomorphology (Wolman and Miller, 1960) or the intermediate disturbance hypothesis in biology (Connell, 1978).

Additionally, the results show that alteration of Kootenay Lake levels by operation of Corra Linn Dam influences recruitment potential in the meandering reach. During dry (low-flow) years for the historic period, stages and recession rates during the recruitment period appear to have been supported in the meandering reach by the historic backwater conditions of the lake, with recruitment potential increasing with proximity to the lake (Fig. 10g). In contrast, mortality increases in the meandering reach after operation of Corra Linn Dam begins (cf. Fig. 10g and h), reflecting adverse stage recession rates directly correlated with lake level manipulation. Similar stage decline patterns occurred in the meandering reach during average and wet years in the pre-Libby Dam period, though they appear to have had less influence on cottonwood recruitment potential (Fig. 10b and e). Operation of Libby Dam has further curtailed recruitment (Fig. 10i) as a result of erratic stage fluctuations during the establishment period in late summer (Figs. 3 and 8i).

However, an interesting trend is apparent in the results for two average years (1997 and 1999), which suggest improved recruitment potential in the braided and meandering reaches compared to other years in the post-Libby Dam period. Experimental flow releases focused on improving the spawning success of white sturgeon below Bonners Ferry have occurred since 1993, and have consisted of increased releases from Libby Dam during the historic

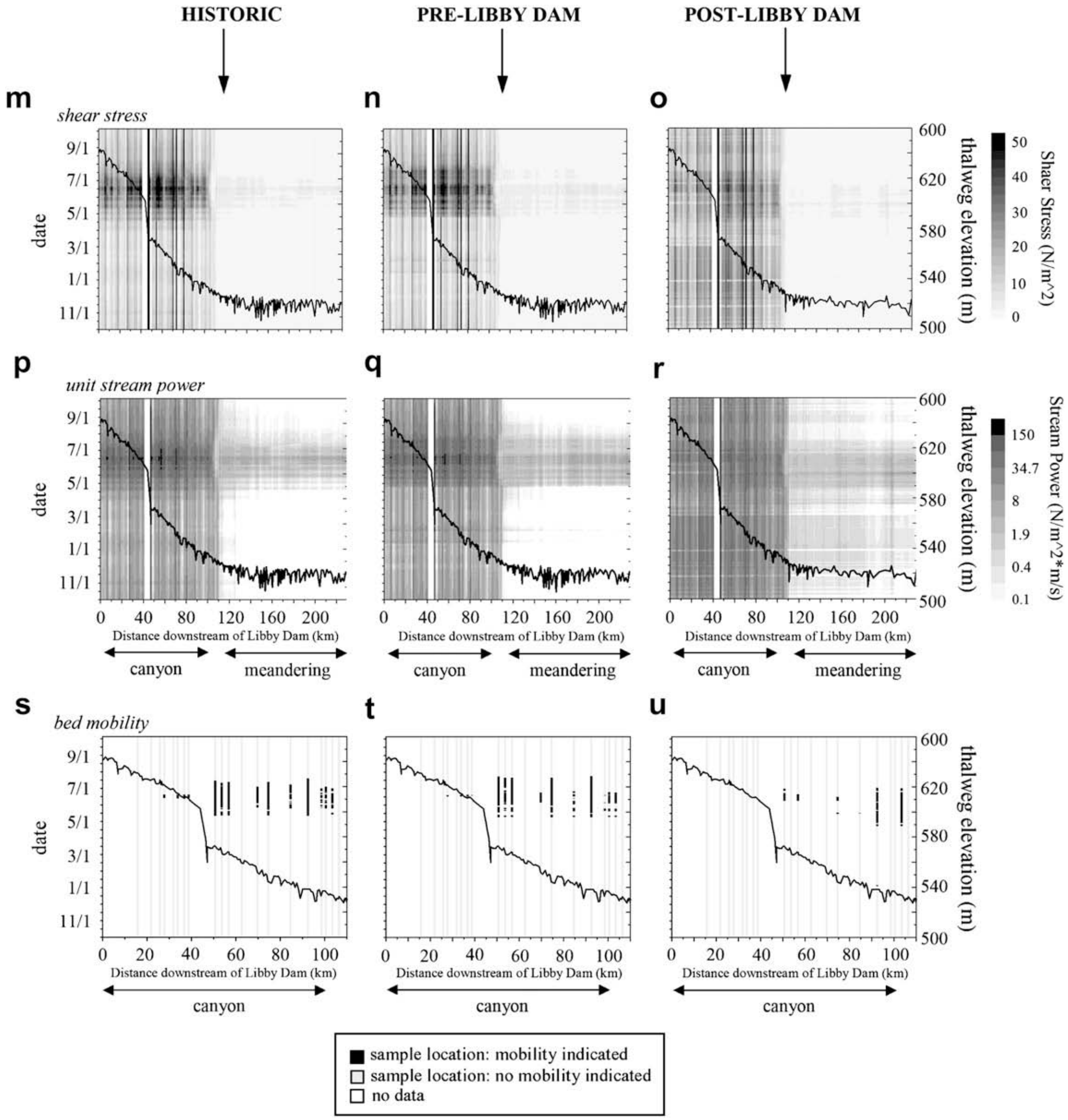

Fig. 8. (*continued*).

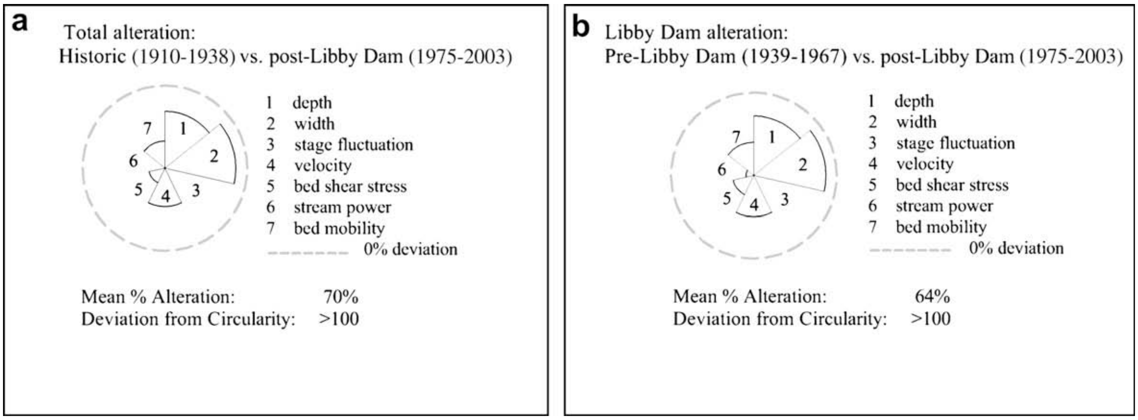

Fig. 9. Pie charts of second-order impacts (altered channel hydraulics and bed mobility) resulting from a) all historic water management activities (historic vs. post-Libby Dam periods) since 1938 (historic vs. post-Libby Dam periods) and b) operation of Libby Dam (pre- vs. post-Libby Dam periods), determined from the mean percent alteration values. Distance from the gray line indicates alteration, while the ratio of the largest piece to the smallest piece (deviation from circularity) gives an indication of uniformity of alteration.

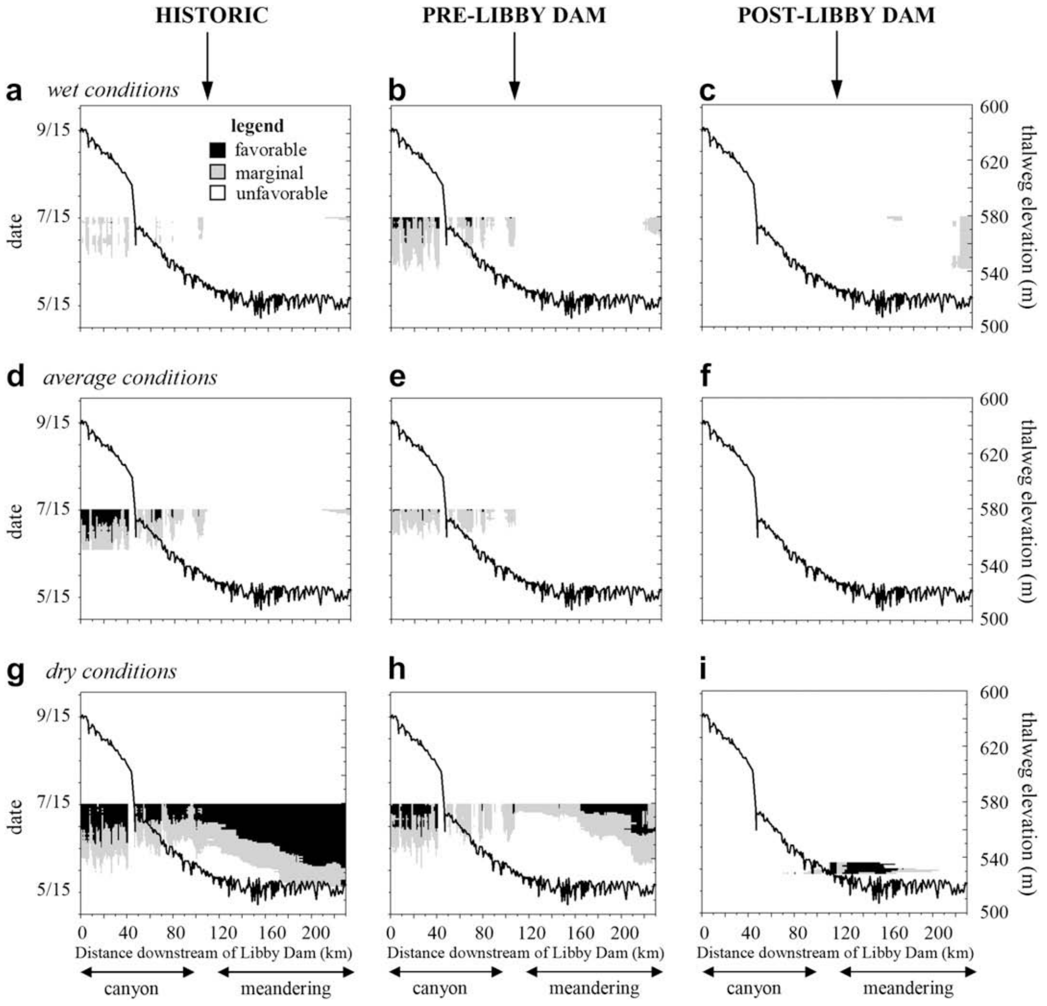

Fig. 10. Spatial and temporal distribution of cottonwood recruitment potential for comparable "dry" water years during a) historic (1931), b) pre-Libby Dam (1945), and c) post-Libby Dam (2001) periods, comparable "average" water years during d) historic (1917), e) pre-Libby Dam (1966), and f) post-Libby Dam (1978) periods, and comparable "dry" water years during g) historic (1931), h) pre-Libby Dam (1945), and i) post-Libby Dam (2001) periods. Black indicates dates where subsequent stage recession curves have mortality coefficients <20 (favorable), gray indicates coefficients between 20 and 30 (marginal), and white indicates coefficients >30 (unfavorable). The heavy black line is the longitudinal profile of the thalweg bed elevation.

snowmelt period. During 1997 and 1999, it appears that the timing of the experimental releases coincided with runoff from tributaries and backwater influences of Kootenay Lake to produce conditions conducive to cottonwood recruitment in the lower half of the study reach. Comparison of hydrographs just below Libby Dam and in the meandering reach during the 1997 experimental releases demonstrates a striking transformation, as the relatively flat, regulated stage at Libby Dam transitions to a pattern similar to that of an unregulated, snowmelt-dominated system within the meandering reach (Porthill), characterized by a sustained peak during the early growing season (mid-May to mid-July) and gradual, sustained recession to baseflow in early fall (Fig. 11a). The pattern of the Porthill hydrograph during this period is similar to that of low-flow years of the historic and pre-Libby Dam periods, which showed high potential for seedling establishment (Fig. 10). Predicted values of cottonwood recruitment further support this observation, with high recruitment potential in the meandering reach during the 1997 experimental releases (Fig. 11b). The extension of the Kootenai Lake backwater into the meandering reach may also be important for attenuating both the flood recession rates and stage fluctuations during these flows.

These results generally support those of earlier field studies on the Kootenai. Polzin and Rood (2000) found severe disruption of cottonwood recruitment below Libby Dam compared to unregulated upstream reaches. Jamieson and Braatne (2001) also found limited recruitment below the dam, but did find occasional groupings of recently recruited cottonwoods in the braided and meandering reaches. They compared nearby gage records to the maturity of the young trees and concluded that the recruitment event had likely occurred in 1997 or 1998, consistent with the findings of this study.

5. Discussion

Over the last several decades, a large body of research has emerged in the fields of aquatic and floodplain ecology that examines relationships between ecosystem processes and the spatial and temporal variability of flow. Many conceptual models have been proposed. For example, Poff et al. (1997) summarized the dependence of multiple trophic levels of species on the 'natural flow regime' – the magnitude, timing, frequency, duration and rate of change of streamflow. Similarly, the 'shifting habitat mosaic' (Arscott et al., 2002; Malard et al., 2002; Stanford et al., 2005) describes the interaction between hydrologic regime and habitat distribution and disturbance, leading to a diversity of habitats. Most recently, the 'riverine ecosystem synthesis' combines concepts of

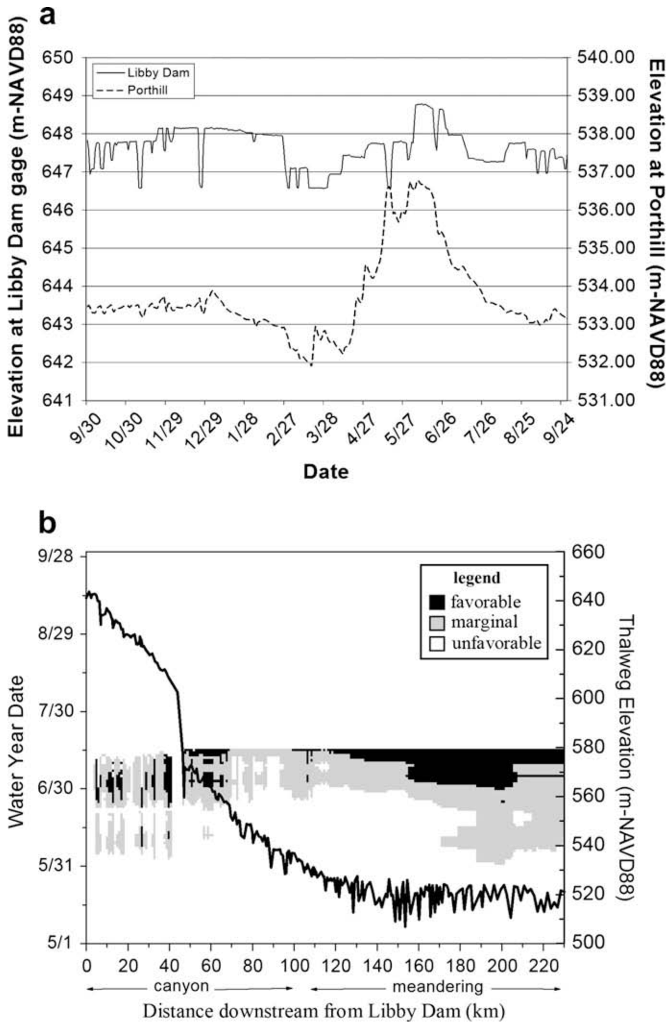

Fig. 11. a) Annual stage hydrographs for Water Year 1997 at locations just below Libby Dam and in the meandering reach (Porthill), based on hydrodynamic model results. b) Corresponding spatial and temporal distribution of cottonwood recruitment potential for 1997 over the study reach. In Fig. 11b, black indicates dates where subsequent stage recession curves have mortality coefficients <20 (favorable), gray indicates coefficients between 20 and 30 (marginal), and white indicates coefficients >30 (unfavorable). The heavy black line is the longitudinal profile of the thalweg bed elevation.

hierarchical landscape patch dynamics and ecological aspects of fluvial geomorphology to examine spatiotemporal biocomplexity in lotic systems (Thorp et al., 2006). Invariably, each of these conceptual models embraces the notion of dynamic distributions of flow and ecosystem processes across space and time (Naiman et al., 2005).

For the Kootenai River, the historic natural flow regime dictated the spatial and temporal distribution of native flora and fauna. Primary and secondary production peaked during the summer months (Holderman and Hardy, 2004), while different species of native fish timed their migrations and fulfilled their life history needs throughout the year, according to their unique attributes (Paragamian et al., 2000, 2001). Riparian trees along the river were highly dependant on seasonal flow patterns for seedling establishment (Braatne et al., 1996; Mahoney and Rood, 1998). The results of our analyses quantify the impacts of Corra Linn Dam and Libby Dam on habitat conditions for native species, showing how these conditions differ from historic values. Like the conceptual models discussed above, our analysis demonstrates the strong, dynamic linkage between flow regime and habitat availability. However, our approach explicitly quantifies the hierarchy of processes controlling ecosystem function over space and time. For example, the assessment of hydrologic alteration demonstrated a marked increase in the number of both low and high pulse counts (Fig. 7). This alteration can clearly be seen in the distribution of daily stage fluctuation (Fig. 8g–i), which shows an erratic pattern throughout the year for the post-Libby Dam era that is in contrast to the highly regular pattern in the pre-Libby Dam era. Erratic stage fluctuation patterns in turn resulted in significantly curtailed riparian recruitment in the regulated era (Fig. 10c, f, i).

Moreover, by utilizing available historical data, we were able to simulate river function under different time periods, allowing us to filter out confounding influences and to isolate the operational impacts of Libby Dam. Most notably, we were able to detect that cottonwood recruitment in the lower half of the study reach had been impacted by downstream regulation of Kootenay Lake and the operation of Corra Linn Dam prior to the closure of Libby Dam. Lastly, the hydrodynamic river modeling approach allowed us to understand the detailed spatial and temporal distribution of operational impacts over an expansive area (Figs. 8 and 10), but also allowed us to combine the specific results for each parameter into a simple index of alteration (Fig. 9).

6. Summary and conclusions

This study quantified impacts of Libby Dam hydropower operations on the spatial and temporal distribution of instream processes over a 233 km reach of the Kootenai River between the dam and Kootenay Lake, after isolating the operational impacts of Corra Linn Dam and other management activities. First-order impacts of Libby Dam were assessed in terms of altered hydrologic regime using the IHA method (Nature Conservancy, 2007). Results show significant alteration of the historic flow regime, with reduced maximum flows during the timing of the historic snowmelt peak, increased minimum flows during the pre-regulation, winter, low-flow period, and increased irregularity of the annual hydrograph. These results suggest that flow parameters and ecological processes that are dependant on the magnitude and timing of flow extremes and on sustained hydrograph trends (i.e., limited irregularity and moderate rates of change), are likely most influenced by Libby Dam.

First-order impacts, in turn, influence the spatial and temporal distribution of second-order impacts to flow parameters (channel hydraulics and bed mobility). An analysis of changes in these parameters showed that daily stage fluctuation and mean stream power were most affected by hydropower operations, with assessed alterations in excess of 100% of pre-regulation values. Bed shear stress and bed mobility showed the next largest change, with maximum flow depth and wetted width least altered. Comparison of second-order changes over different time periods indicates that impacts from Libby Dam dominate, accounting for 91% of the total change in flow and bed mobility parameters.

Third-order impacts were assessed in terms of potential changes in cottonwood recruitment due to altered stage recession patterns during the post-flood establishment period (Mahoney and Rood, 1998). The results suggest that the greatest potential for seedling recruitment historically occurred during low-flow years. Furthermore, a multi-year pattern for cottonwood establishment may have existed prior to emplacement of the hydropower facilities; high-flow years prepared nursery sites that were subsequently colonized during lower flow years that were more favorable for germination and establishment.

Results further show that alteration of Kootenay Lake levels by operation of Corra Linn Dam inhibited cottonwood recruitment potential in the meandering reach during the pre-Libby Dam period. Drawdown of Kootenay Lake during late summer caused sustained stage recession rates in the meandering reach that exceeded documented tolerances for cottonwood seedlings. Following closure of Libby Dam, cottonwood recruitment was further curtailed by regulation throughout the study reach, principally as a result of erratic stage fluctuations resulting from ramping practices for hydropower operation and increased fall and winter flows.

We also find that recent flow releases aimed at restoration of native fishes may have contributed to conditions favorable for cottonwood recruitment in the meandering reach. These favorable hydrograph patterns likely reflect a combination of factors, including enhanced releases for fish recovery, tributary inputs during the snowmelt period, and attenuation of stage fluctuation (i.e., damping of Libby Dam ramping patterns) in the backwater-controlled meandering reach. These results hold promise for riparian restoration efforts in the braided and meandering reaches of the river. Conditions conducive to riparian recruitment may be attainable during some years, though it is unknown whether adequate nursery sites exist.

7. Implications for measuring dam impacts

Process-based, hierarchical analyses, such as the example presented in this study, provide a powerful tool for assessing operational impacts of dams on physical processes and consequent ecosystem function. With this approach, physical drivers and biological responses can be displayed in space and time, with the potential for isolating specific operational impacts. This approach provides an advantage over purely empirical techniques because it allows process-based extrapolation over space and time beyond individual observations. The approach is also unique in that the linkages between orders of impact are explicitly simulated, which is useful for exploring and developing better understanding of these linkages. Once assembled and calibrated, the simulation tools may also be used in a predictive manner to quantitatively evaluate future management and restoration strategies. By helping river managers understand and quantify the spatially and temporally distributed effects of management adjustments within a study area, critical questions such as how much, when, and for how long can be assessed. Furthermore, the relative influence of confounding factors that might accentuate or counteract a restoration action can be determined.

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