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Kootenai River velocities, depth, and white sturgeon spawning site selection – a mystery unraveled?

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Summary

The Kootenai River white sturgeon *Acipenser transmontanus* population in Idaho, US and British Columbia (BC), Canada became recruitment limited shortly after Libby Dam became fully operational on the Kootenai River, Montana, USA in 1974. In the USA the species was listed under the Endangered Species Act in September of 1994. Kootenai River white sturgeon spawn within an 18-km reach in Idaho, river kilometer (rkm) 228.0–246.0. Each autumn and spring Kootenai River white sturgeon follow a 'short two-step' migration from the lower river and Kootenay Lake, BC, to staging reaches downstream of Bonners Ferry, Idaho. Initially, augmented spring flows for white sturgeon spawning were thought to be sufficient to recover the population. Spring discharge mitigation enhanced white sturgeon spawning but a series of research investigations determined that the white sturgeon were spawning over unsuitable incubation and rearing habitat (sand) and that survival of eggs and larvae was negligible. It was not known whether post-Libby Dam management had changed the habitat or if the white sturgeon were not returning to more suitable spawning substrates farther upstream. Fisheries and hydrology researchers made a team effort to determine if the spawning habitat had been changed by Libby Dam operations. Researchers modeled and compared velocities, sediment transport, and bathymetry with post-Libby Dam white sturgeon egg collection locations. Substrate coring studies confirmed cobbles and gravel substrates in most of the spawning locations but that they were buried under a meter or more of post-Libby Dam sediment. Analysis suggested that Kootenai River white sturgeon spawn in areas of highest available velocity and depths over a range of flows. Regardless of the discharge, the locations of accelerating velocities and maximum depth do not change and spawning locations remain consistent. Kootenai River white sturgeon are likely spawning in the same locations as pre-dam, but post-Libby Dam water management has reduced velocities and shear stress, thus sediment is now covering the cobbles and gravels. Although higher discharges will likely provide more suitable spawning and rearing conditions, this would be socially and politically unacceptable because it would bring the river elevation to or in excess of 537.66 m, which is flood stage. Thus, support should be given to habitat modifications incorporated into a management plan to restore suitable habitat and ensure better survival of eggs and larvae.

Introduction

Sturgeon species (Acipenseridae) are well suited to local adaptations of riverine life histories that include a river as a part of or their entire life history (Bemis and Kynard, 1997). However, sturgeon adaptations to riverine habitats are compromised with the world-wide construction and operation of dams (Votinov and Kas'yanov, 1978; Parsley et al., 1993; Hensel and Holčík, 1997). Construction and operation of dams have resulted in fragmented populations, reduced or eliminated spawning and rearing habitat, altered annual discharge patterns, temperatures, nutrient releases, flood plain connectivity and more (Alekperov, 1969; Khoroshko, 1972; North et al., 1993; Parsley and Beckman, 1994; Auer, 1996; Nilo et al., 1997; Anders et al., 2002; Beamesderfer and Farr, 1994; Beamesderfer et al., 1995). Changes in sturgeon population densities brought Beamesderfer and Farr (1997) to state 'life history traits that have proven adaptive over the last 100 million years are now a disadvantage in the face of habitat changes.'

In Idaho, USA the white sturgeon *Acipenser transmontanus* is native to the Snake and Kootenai rivers and can be found in the lower reaches of the Clearwater and Salmon rivers (Simpson and Wallace, 1982). The Kootenai River white sturgeon was given Endangered Species status in Idaho and MT, USA on 6 September 1994 (USFWS, 1994; Duke et al., 1999). This population of white sturgeon received Endangered Species status because it became recruitment-limited (Partridge, 1983; Apperson and Wakkinen, 1992) soon after the Libby Dam was completed by the U.S. Army Corps of Engineers (USACE) in 1972 to become fully operational shortly after 1974. Operation of Libby Dam seriously modified the discharge pattern of the Kootenai River by lowering flows during spring when white sturgeon spawned (Partridge, 1983; Apperson and Wakkinen, 1992; Duke et al., 1999).

Each autumn and spring the transboundary Kootenai River white sturgeon follow a 'short two-step' migration pattern (Bemis and Kynard, 1997) from the lower river and Kootenay Lake in British Columbia (BC), to staging reaches downstream of Bonners Ferry, Idaho (Fig. 1). Typically the river stage rises and the temperature increases during spring and adult white sturgeon migrate to the Libby Dam area spawning reach (rkm 228.0–246.0) (Paragamian and Kruse, 2001) where spawning takes place at river temperatures of about 8°C and warmer. Initially, augmented spring flows for white sturgeon spawning were thought to be sufficient to recover the population (Paragamian et al., 1996). Spring discharge mitigation during enhanced white sturgeon spawning (Paragamian et al., 2001) and a series of research investigations determined their migration and spawning pattern (Paragamian and Kruse, 2001); micro spawning habitat (Paragamian et al., 2001); the discharge and temperatures necessary for spawning to occur

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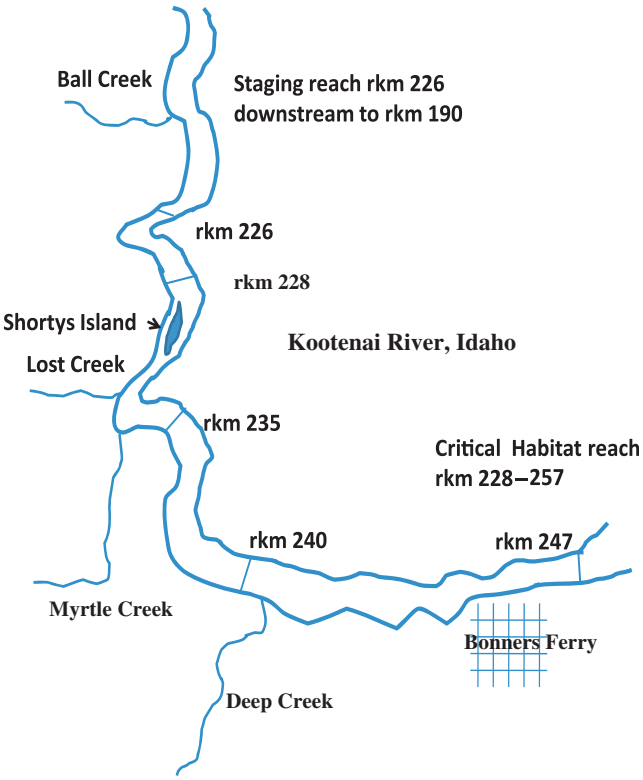

Fig. 1. Location of Kootenai River, Idaho primary study reach rkm 228–247, main tributary streams, upper reach of staging reach, and lower reach of designated critical habitat

(Paragamian and Wakkinen, 2002); but that white sturgeon eggs were, however, likely suffocating under sand and silt substrates (Paragamian et al., 2001; Kock et al., 2006). It was known that more suitable spawning substrates were further upstream but it was not known if white sturgeon were spawning in the same historical locations or if they were no longer migrating to suitable locations because of the altered river hydrology. It was apparent that results of standard fisheries investigations alone were unable to define more specifically what kind of fluvial hydrologic processes and habitat changes in the Kootenai River had occurred because of Libby Dam operations. Nor was it possible to determine how it related to white sturgeon behavior and spawning site selection.

Because the empirical relationship between hydraulic conditions and white sturgeon spawning remained unclear, we describe a multi-disciplined approach. This was accomplished by the teaming of fisheries scientists with fluvial hydrologists of the US Geologic Survey (USGS) and combing hydrologic data with known white sturgeon spawning data to help resolve an important issue to Kootenai River white sturgeon recovery: how the changes that have occurred to velocities, sediment transport and bathymetry post-Libby Dam may be affecting spawning site selection. We believed a conceptual model of white sturgeon spawning behavior, based on hydraulic parameters in the current spawning reach, might lead to a better understanding of why white sturgeon do not appear to spawn further upstream in the braided reach, or migrate through the braided reach to spawn further upstream in the canyon reach where there are more suitable substrates (Parsley and Beckman, 1994). This manuscript is a fisheries interpretation of a previous hydrophysiographic document (McDonald et al., 2006).

Study site

The Kootenai River is in the upper Columbia River basin of the USA and Canada and within the northern Rocky Mountains physiographic province (Fenneman, 1946). This region is characterized by northwest-trending mountain ranges and valleys. The Kootenai River is 721 km long and the basin is 45 584 km^2. The river originates in Kootenay National Park, BC, flows south into Montana and turns northwest near the site of Libby Dam, at river kilometer (rkm) 352.4. Kootenai Falls, 42 km below Libby Dam, is thought to be an impassable barrier to sturgeon. As the river flows through the northeast corner of the Idaho panhandle, there is a gradient transition. The canyon reach (rkm 272–252) has an average gradient of 0.6 m km^{-1} with velocities often higher than 0.8 m s^{-1}. Downriver the river slows in the braided reach with velocities usually < 0.4 m s^{-1} (rkm 252–246). Further downstream the average gradient of the meander reach (rkm 246–120) is 0.02 m km^{-1} (0.1 ft mi^{-1}) the channel deepens, and the river meanders north through the Kootenai River valley. As the river flows through the northeast corner (rkm 265.0) it shifts to the north and enters Kootenay Lake, BC (rkm 120.0), where it flows out through the western arm and eventually to the Columbia River. Our primary study reach for this investigation was from rkm 228.0 to 247.0 (Fig. 1).

Methods

White sturgeon egg collections

White sturgeon eggs were collected during rising, receding, and steady river flows from 1994 through 2002. White sturgeon eggs were sampled with 70–100 sampling mats each season (Paragamian et al., 2001; Paragamian and Wakkinen, 2002) as described by McCabe and Beckman (1990). The mats were steel frames with dimensions of 0.6×0.9-m with woven furnace filter material about 2.5-cm thick. The mat placement, deployment, and standardization scheme are described in Paragamian et al. (2001). Mats were usually set from early-May through the first week in July, pulled daily, examined for presence of eggs, and redeployed. Sampling location was noted to the nearest 0.1 km for all mats including mats that did not collect white sturgeon eggs. Eggs were removed from the mats and stored in labeled vials containing formalin or alcohol solution. Effort for each mat was recorded as one mat-day and was a 24-h set. Egg collections were standardized for our comparisons to hydrologic variables of river depth and velocity. Effort and egg collections were further calculated per 0.1 river km, and collected eggs were divided by days of effort to obtain catch per unit effort (CPUE).

Kootenai River hydrologic and sediment studies

To determine the historic aspect of hydrologic changes in the Kootenai River in both pre- and post-Libby Dam channel substrate, sediment transport and velocities were studied, then compared to egg collection locations. Several studies characterized the channel substrate in the spawning reach (rkm 228–247, Fig. 1). Barton (2004) used vibra- and piston-cores collected uniformly along the length of the Critical Habitat reach, rkm 228–257 (USFWS, 2008). Barton (2004) based his studies on the grain-size and stratigraphy of the cores. A subsequent vibra-core study in 2004 was also included to better characterize the stratigraphy of the buried grave-cobble zone for 1D-sediment transport modeling (Berenbrock and Bennett, 2005a).

Kootenai River velocities, depth, shear stress, and 2-D model

The USGS multidimensional surface-water modeling system (MD_SWMS) was used to simulate water-surface elevation, velocity, and boundary (bed) shear stress throughout most of the 29-rkm Critical Habitat reach. By studying shear stress, the degree of sediment transport and scouring of the river bottom could be estimated based on river velocity at varying elevations (discharge). Subsidiary methods were used to simulate both the motion of sediment and morphologic evolution or change of the riverbed. MD_SWMS is a Graphical User Interface (GUI) developed by the USGS (McDonald et al., 2008) for hydrodynamic models. FaSTMECH is one computational model within MD_SWMS (Nelson et al., 2003). FaSTMECH includes a 2-D, vertically averaged model and a sub-model that calculates vertical distribution of the primary velocity and the secondary flow about the vertically averaged flow. Details of the model development, calibration and verification for the Kootenai River can be found in Barton et al. (2004, 2005). With the 2-D model and white sturgeon egg collection and GPS location information we could estimate depth and maximum velocity of the river in collection locations.

To compare model simulations of depth and velocity over a similar range we picked five time-periods from the historical record where the discharge was both relatively constant for two or more days and fell within the range of estimated spawning events. The solution for velocity and depth at each of the five modeled discharges was probed at an interval of 0.1 rkm along the thalweg and the minimum, average, maximum, and probed point were recorded.

The combination of the 2-D modeling, sediment studies, and velocities were used in the sediment transport models. The only year with natural recruitment measured by catch of 20 or more Kootenai River white sturgeon during the post-dam period was 1974 (Partridge, 1983). Uniquely, that year had both high discharge ($\sim$1300 $m^3\ s^{-1}$) and relatively long duration (14 days) compared to any other year in the post-dam record. To test our 2-D model we used the 1974 hydrograph in a sediment-transport simulation to explore the potential of high flows to remove sand and expose coarse gravel periodically or to explore a suitable substrate for egg adhesion. We idealized the hydrograph to a steady-flow period of 14 days at a constant discharge of 1300 $m^3\ s^{-1}$, corresponding to the high-flow period prior to the usual spawning season, to evaluate the spatial pattern and magnitude of erosion and deposition in the reach where sturgeon spawn. Several of the specific assumptions used in the model were: (i) the transport was assumed to be in equilibrium with the riverbed, (ii) a mean grain-size (0.2 mm) equivalent to the existing bed was used, (iii) only a single grain-size was considered, and (iv) we used the Engelund–Hansen total load equation to determine the transport rate. Details of the sediment transport model can be found in Nelson et al. (2003).

Model of white sturgeon spawning behavior and hydraulic parameters

When looking at the suitability of spawning habitat based on velocity, the spatial distribution of velocity throughout the river at the time of spawning was used rather than a range of velocity magnitude measured at various points in space and time in which discharge may vary substantially. The micro-habitat of Kootenai River white sturgeon had been previously described as water depths within the main channel usually exceeding 5 m, velocities of 0.5–1.0 m s^{-1}, sand substrate, and temperatures frequently between 8.5 and 12°C (Paragamian et al., 2001). To test the possible observation of a relationship between egg CPUE and depth and velocity we used spatial correlation (Rahel and Jackson, 2007) between spawning location and maximum velocity and maximum depth.

Results

White sturgeon egg collection effort and locations

We expended a total of 28 833 mat-days of sampling effort between 1994 and 2002 to verify natural spawning of white sturgeon in the Kootenai River study reach. Sampling effort ranged from 2401 mat-days in 1994 to 4448 mat-days in 1996 (Table 1 and Fig. 2).

White sturgeon egg sampling accounted for an annual total range of 75 eggs in 1997 to 483 in 1998, with a CPUE (eggs per net days) range of 0.017 in 1997 to 0.0887 in 1994 (Table 1). All eggs were collected between rkm 228 and 246. There appeared to be four consistent reaches where sturgeon eggs were collected: 228.5–231.5, 232.0–233.9, 235.8–237.5, and 237.9–240 but less frequently at 245.0–245.9 (Fig. 2).

Kootenai River channel substrate, velocity, depth shear, stress, and 2-D model

Based on grain-size and stratigraphy of cores, the Kootenai River study reach was classified into three broad zones: a sand-gravel-cobble zone in the braided reach downstream from Bonners Ferry (rkm 246–244.5); a buried gravel-cobble zone between 241 and 244.5 rkm; and a sand zone with isolated lenses of buried cobble downstream from 241 rkm in the meander reach (Fig. 1). The vibra-core study in 2004 of the buried grave-cobble zone for 1D-sediment transport modeling found that the meander reach is also characterized by smaller lenses of buried coarse cobbles and gravels. In addition, field observations identified gravel-cobble sized material occurring at the confluence of three small tributaries with the Kootenai River in the downstream region of the study area: Deep, Myrtle and Lost creeks (Fig. 1). Presumably, periodic large floods would provide a limited supply of coarse material to the river from these small tributaries. The gravel-cobble substrate within the meander and braided reaches may have historically provided coarse material to the meandering reach. Of

Table 1
Summary of total sampling mat effort (day), total number of eggs collected, and catch per unit effort (CPUE)

	Year								
	1994	1995	1996	1997	1998	1999	2000	2001	2002
Mat-days	2401	3278	4448	4256	3759	3387	2676	2823	1805
Total number eggs	213	162	349	75	483	184	186	139	296
CPUE	0.0887	0.0494	0.7846	0.0176	0.1285	0.0543	0.0695	0.0492	0.1640

particular interest to this study is the potential of the greater magnitude and duration of pre-dam flows to expose the buried coarse substrate in the existing spawning reach.

Total discharges during mitigation for white sturgeon spawning (May–June) in the Kootenai River ranged from about 600 to 1200 $m^3 s^{-1}$. Peaks in average daily discharge at Bonners Ferry during the spawning seasons were 582, 944, 1294, 1162, 969, 1005, 884, 393, and 1155 $m^3 s^{-1}$ for the years 1994 through 2002, respectively. To simulate the maximum velocity for each of the 9 years we modeled five discharges at 500, 770, 1500, 1400, and 1600 $m^3 s^{-1}$ (Fig. 3), along with the white sturgeon egg CPUE (Fig. 3).

We also modeled the discharge of 1300 $m^3 s^{-1}$ during the 1994 spawning season (Partridge, 1983) and found the beginning, ending, and changes in topography, respectively, for a small reach of meandering river at 234–235 rkm (Fig. 4). This reach lies within the present spawning reach. In modeling we found a generalized scour of approximately 1 m by the negative change in elevation throughout the outside of the meander bend and more locally extensive scour of up to approx. 3 m near the apex of the meander bend. Based on the core records in Barton (2004) the scour would be sufficient to at least partially expose some buried gravel and cobble. However, these results should be viewed with some degree of caution.

Model of white sturgeon spawning behavior and hydraulic parameters

Qualitatively (McDonald et al., 2006) there appeared to be a positive correlation between spawning location and both maximum velocity and maximum depth (Figs 3 and 5). We performed a spatial correlation between spawning location and maximum velocity and maximum depth to test this observation by shifting velocity and depth each over a 1.0 rkm range both upstream and downstream by 0.1 rkm increments. The resulting correlations, reported as R^2 values and with significance at the 99th percentile, while not particularly robust revealed broad regions of positive correlation centered on the position of maximum velocity and depth. In addition, the correlations fell off faster when shifting the velocity and depth downstream. Correlations calculated between the average velocity and average depth but not reported here, were not as conclusive. The correlation results suggest that the white sturgeon are keying in on spawning at regions of highest

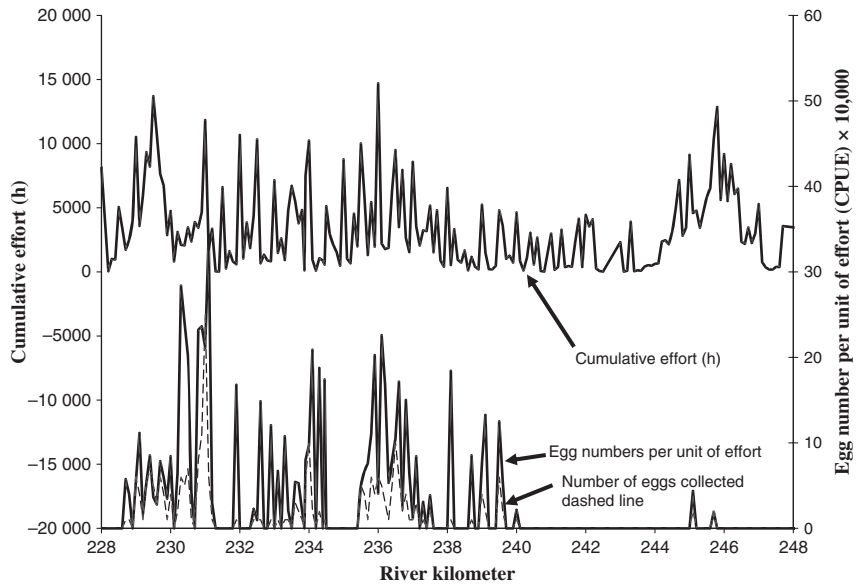

Fig. 2. Total number of egg collections 1994–1999 at 0.1 rkm increments, Kootenai River white sturgeon primary spawning reach (rkm 228.7–239.9) and secondary location (rkm 245–245.9)

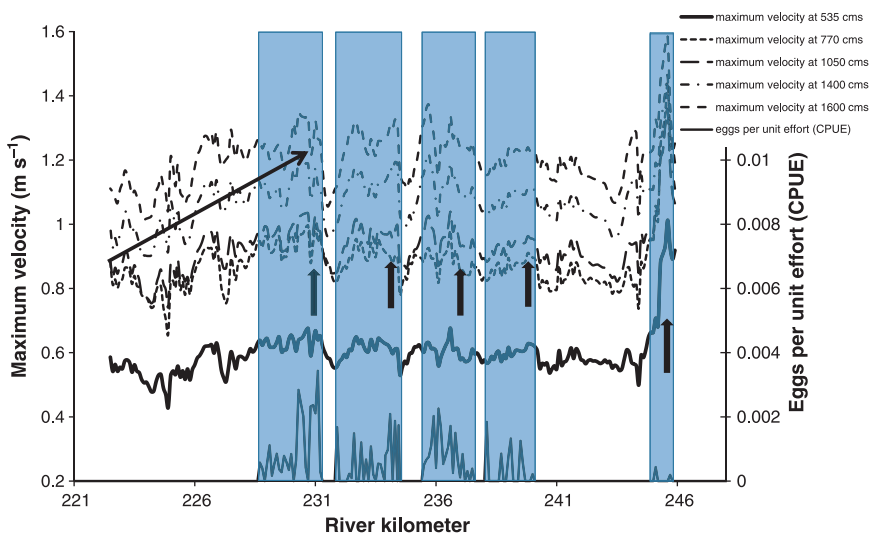

Fig. 3. Mean maximum velocity by 0.1 km class intervals 1994–1999 for five discharge (cms) values, primary spawning reach of Kootenai River white sturgeon (rkm 228.7–239.9) and secondary location (rkm 245–245.9) (modified after Barton et al., 2006). Shaded areas = egg collection locations. Black vertical arrows = location of accelerating velocities; angled arrow = where average velocities tend to increase from a lower reach to the spawning reach

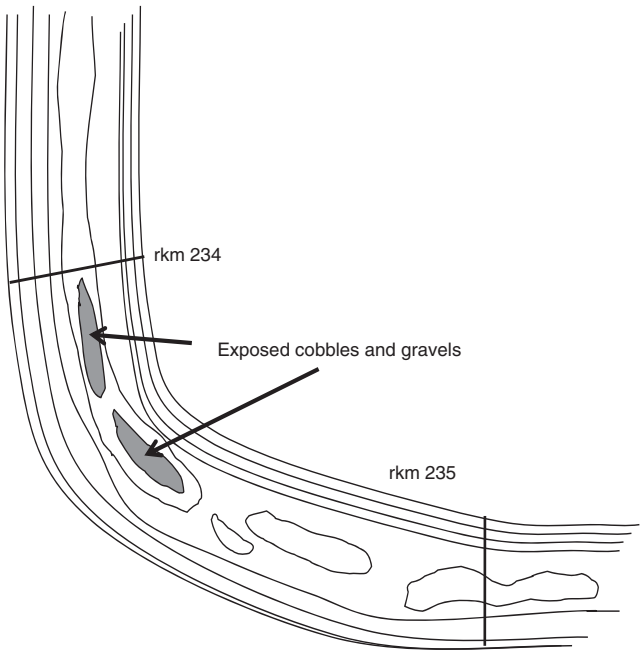

Fig. 4. Rendition of Kootenai River depth contours at 5 m depth intervals, near mouth of Myrtle Creek (rkm 233.5–234.7) and area of exposed gravels and cobbles after modeled scouring in 1974 of 1300 $m^3 s^{-1}$

velocity and greatest depth while eggs disperse gradually downstream with the highest concentrations at the spawning sites. With modeling of the river below the spawning reach (rkm 228), showed that the river was slower for the same discharges and that depth tended to be shallower (Figs 3 and 5).

Discussion

The major objective of our investigation was to determine if white sturgeon in the Kootenai River, post-Libby Dam, were still spawning in their historic locations. By integrating the disciplines of fisheries and fluvial geology we conclude that they are spawning in pre-Libby Dam locations but that post-dam river regulations had rendered the meander reach habitat / Critical Habitat (USFWS, 2008) unsuitable for incubation and rearing of white sturgeon progeny, resulting in recruitment failures.

Our analysis suggested that Kootenai River white sturgeon are spawning in areas of highest available velocities and depths over a range of flows. Regardless of the discharge, the locations of accelerating velocities and maximum depth do not change and spawning locations remain consistent in the meander reach. While the importance of velocity has been presented in other studies of white sturgeon spawning habitats (Parsley et al., 1993; McCabe and Tracy, 1994; Parsley and Beckman, 1994), in this study we present a slight modification by suggesting there is not a particular threshold velocity or even a specific range of velocity that sturgeon key on. Rather, all other things being considered such as sufficient discharge, temperature, and receding flows (Paragamian and Wakkinen, 2002; V. L. Paragamian, unpubl. data) that they appear to key in on the highest velocity and depth within the spawning region for the given discharge that is occurring. Paragamian and Wakkinen (2002) found that average daily flow for spawning events from 1994 through 2000 ranged from 141 to 1265 $m^3 s^{-1}$, but that most (51%) spawning took place from 630 to 1135 $m^3 s^{-1}$. This interpretation suggests that spawning fish will seek out the best-perceived location to release gametes, given the current environmental conditions of river regulation. Regardless, the sandy substrate in the spawning reach likely remains a major bottleneck by increasing the mortality of eggs, which require a coarser substrate to incubate successfully (Parsley and Beckman, 1994; Kock et al., 2006).

Although spawning of white sturgeon in the braided reach (above the meander reach) of the Kootenai River has occurred, there has been no detectible consistency because the braided reach appears to be a secondary location despite the presence of more suitable substrates (Paragamian and Wakkinen, 2002). Under current flow conditions in the Kootenai River white sturgeon must move through many areas of relatively higher velocity or deeper water before entering the braided reach. Based on the analysis presented here, we identified that a velocity contrast exists between the relatively high velocity braided reach and the lower velocity meandering reach. There are even more suitable conditions for white sturgeon spawning further upstream in the canyon reach. At the highest discharges associated with pre-dam peak flows, the difference between the existing post-dam managed

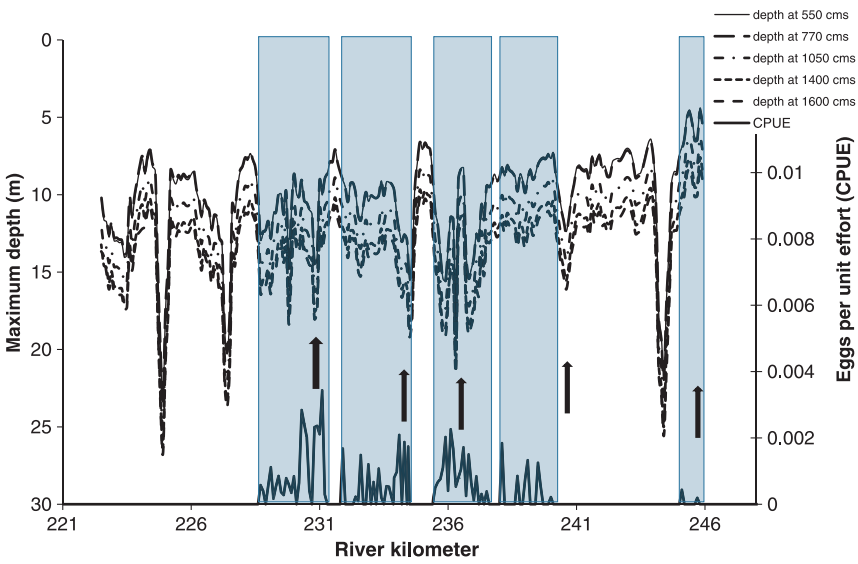

Fig. 5. Mean maximum depth by 0.1 km class intervals by date category, 1994–1999 for five discharge (cms) values, primary spawning reach of Kootenai River white sturgeon (rkm 228.7–239.9) and secondary location (rkm 245–245.9) (modified after Barton, 2006). Shaded areas = egg collection locations. Black vertical arrows = location of deepest water

flow regime and the natural pre-dam flow regime may have encouraged the white sturgeon to migrate further upstream and spawn over the more suitable substrate. Unfortunately, there is no historical evidence to show whether or not white sturgeon ever spawned within the two reaches upstream. Rust and Wakkinen (2005) experimented for 2 years by transporting mature adults to the canyon reach prior to the spawning season. One spawning event was documented, but most white sturgeon returned downstream to their capture location soon after release or to Kootenay Lake.

Modeling of discharges during the spawning season of 1974 indicated that discharges of 1300 $m^3 s^{-1}$ and more would scour suitable reaches of incubation and rearing cobbles and gravel, as described by Parsley and Beckman (1994). During June 2006 a series of unexpected rain on snow events and warm weather caused the USACE to spill from Libby Dam, which in turn caused the Kootenai River in the white sturgeon spawning reach to attain a discharge of over 1700 $m^3 s^{-1}$, exceeding the flood stage of 537.66 m and resulting in the most significant release from Libby Dam since completion. A 40-day sustained discharge above 1000 $m^3 s^{-1}$ occurred between 17 May and 25 June 2006. The flow reached a mean daily discharge of 1730 $m^3 s^{-1}$ on 18 June and spent 12 days above 1300 $m^3 s^{-1}$ during the 11–22 June period. After floodwaters receded we examined several of the spawning locations and areas of predicted scouring and found cobbles and gravels. We also sampled downstream of three small tributaries, including Myrtle, Lost, and Ball creeks. The potential for these tributaries to deliver coarse material to the Kootenai River is supported by the series of vibra-cores collected in 2000 and 2004 (Barton, 2004; Berenbrock and Bennett, 2005). Cores collected downstream of both Lost and Myrtle creeks either indicated gravel from pitted core bottoms or collected gravel at the bottom of the core. These gravels were covered by 0.5–2.0 m of sand. One exposed gravel/cobble sub-bottom was over 12 m in width and 61 m in length. Prior to the Libby Dam, discharges in the Kootenai River during the spring freshet averaged over 1600 $m^3 s^{-1}$ and on occasion reached 2800 $m^3 s^{-1}$. These results add substantial credibility to the hypothesis that white sturgeon in the Kootenai River are spawning over historic spawning locations, but that post-Libby Dam hydrology has rendered this important reach inhospitable to egg incubation and larval rearing.

Although we have relatively good confidence in the pattern of scour and deposition, the magnitude of the change is much less certain for several reasons. As stated earlier, sediment transport is assumed to be in equilibrium with the bed shear stress at the upstream cross-section of the model reach. However, depending on the upstream sediment supply, the scour could be greater or less. The elevation of the topography at any point in time depends on the preceding history of flow and sediment supply; we started with the topography as measured at a specific point in time. The results clearly indicated the potential for discharge with magnitude, duration, and shear stress as that in 1974 to scour the bed and expose limited patches of suitable substrate.

Results of a 1-D model of flow in the lower braided reach (Berenbrock, 2005) show a sharp monotonic increase in average velocity by a factor of two over most of the downstream meander reach from rkm 249. The other region of relatively high velocity is found in the transition between the braided and meandering reach near Bonners Ferry. Here, there are consistently higher velocities than any in the meandering reach. Thus it appears that white sturgeon are keying on regions of high velocity, as they move into and through the current spawning reach.

Paragamian et al. (2001) noted that the Kootenai River white sturgeon use a longer reach of river to spawn than do white sturgeon elsewhere. Perhaps this is an adaptation to the Kootenai River where the natural variability in flow magnitude and duration from one year to another was at times sufficient to scour the bed and expose coarse substrate. Depending on the downstream transport of coarse material from the locations upstream and local inputs of coarse material from tributaries, the location of suitable substrate varied from one year to another (Hanskki, 2002).

To bring the analysis to a conclusion and tie together both the hydraulic cues used for spawning site selection and the ability of high flows to scour the bed and expose suitable substrate for egg incubation, the following observation is made. The white sturgeon appear to seek the highest velocity and depth regions within the meandering reach to spawn, as indicated by the spatial correlation analysis (McDonald et al., 2006). The spatial location of these regions remains relatively constant at all flows through the region, with highest velocity changes depending on the discharge, but most post-Libby Dam discharges have been incapable of scouring and exposing areas that have suitable incubation and rearing habitat.

For the Kootenai River our recommendations for spring discharge approximating 1600 $m^3 s^{-1}$ or more for a period of 2 weeks is socially and politically unacceptable because it would bring the river elevation to or exceed 537.66 m, which is flood stage. It is beyond the scope of this paper to weigh the tradeoffs of economic and possible human losses by flood damage to the biological benefits of higher discharges. A more acceptable recommendation would be the support of a large-scale habitat enhancement to the spawning reach. The results of our investigation may have further implications for populations of white sturgeon in the Snake (Lepla and Chandler, 1997), Sacramento (Kohlhorst, 1976), and Columbia (Beamesderfer et al., 1995; UCWSRI, 2002) rivers that have been fragmented by dams.

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