MODELING HYDRAULIC AND SEDIMENT TRANSPORT PROCESSES IN WHITE STURGEON SPAWNING HABITAT ON THE KOOTENAI RIVER, IDAHO

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Abstract: The Kootenai River white sturgeon currently spawn (2005) in an 18-kilometer reach of the Kootenai River, Idaho. Since completion of Libby Dam upstream from the spawning reach, there has been only one successful year of recruitment of juvenile fish. Where successful in other rivers, white sturgeon spawn over clean coarse material of gravel size or larger. The channel substrate in the current spawning reach is composed primarily of sand and some buried gravel; within a few kilometers upstream there is clean gravel. We used a 2-dimensional flow and sediment-transport model and the measured locations of sturgeon spawning from 1994-2002 to gain insight into the paradox between the current spawning location and the absence of suitable substrate. Spatial correlations between spawning locations and the model simulations of velocity and depth indicate the white sturgeon tend to select regions of highest velocity and depth within any river cross-section to spawn. These regions of high velocity and depth are independent of pre- or post-dam flow conditions. A simple sediment-transport simulation suggests that high discharge and relatively long duration flow associated with pre-dam flow events might be sufficient to scour the sandy substrate and expose existing lenses of gravel and cobble as lag deposits in the current spawning reach.

INTRODUCTION

The Kootenai River white sturgeon is both physically isolated and genetically distinct from other white sturgeon populations in the Columbia River. Following the completion of Libby Dam, Montana, in 1972, the only year of significant recruitment in the population occurred in 1974, one year prior to full power plant operation in 1975. In ensuing years, a small number of juvenile fish have been found but their abundance is not enough to sustain the population. In 1994 the Kootenai River white sturgeon were listed as endangered and further protection was obtained in 2001 through the designation of 18 river kilometers (rkm) of Critical Habitat downstream from Bonners Ferry, Idaho (rkm 228-246). Monitoring of both the physical location of adult white sturgeon through telemetry studies and the spawning locations by the collection of eggs has shown this reach to be the main region of spawning (Paragamian and others, 2001).

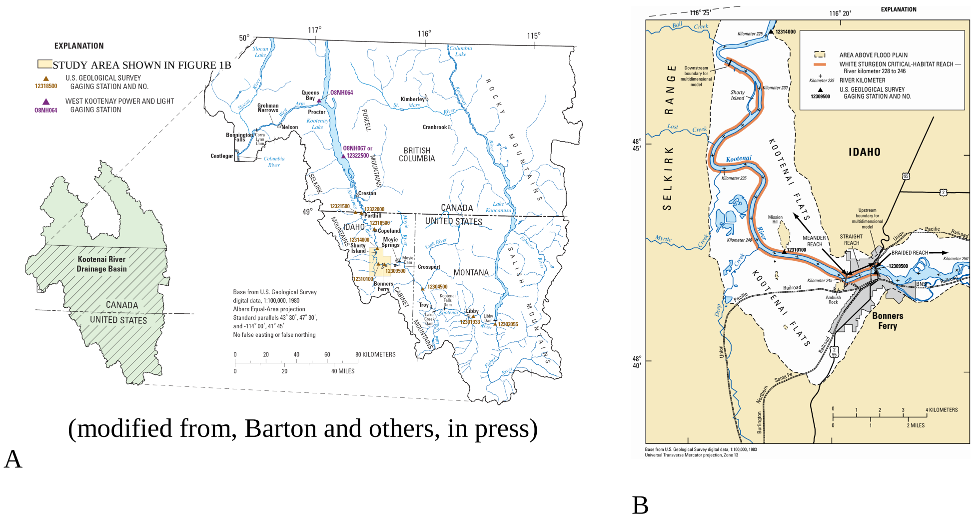
White sturgeon spawn by broadcasting their eggs which become adhesive shortly after exposure to water. Where successful spawning occurs in other river systems, these eggs attach to coarse substrate composed of gravel and larger-sized sediment. While the sturgeon are documented to successfully spawn in the Critical Habitat reach, the exposed river substrate under most flow conditions is dominantly composed of fine sand with large migrating dunes. Spawned eggs are presumed to settle onto the bed, become covered in the fine sand, or buried in the trough of migrating dunes resulting in suffocation. Interestingly, within a few kilometers upstream from the current (2005) spawning locations, the river is braided, relatively shallow, and has suitable substrate composed mostly of gravel and cobble.

Successful spawning and recruitment of Kootenai River white sturgeon is a complicated biologic process with the hydraulic and sediment-transport characteristics playing a contributing role to the success of hatching after deposition. Several hypotheses relating to the hydraulic and sediment transport characteristics of the Kootenai River have been put forth as possible explanations to the decline of successful recruitment (Duke and others, 1999) in this system. First, in the post-dam period, the loss of naturally occurring high spring flow in addition to lower Kootenay Lake stages may have shifted the hydraulic cues the fish use to initiate spawning further downstream into the current spawning reach. In other words, prior to Libby dam, higher lake levels or greater backwater extent and river stage encouraged the fish to spawn further upstream in the braided reach. Second, the higher pre-dam discharge may have mobilized and scoured the bed sufficiently in the existing spawning reach to expose coarse-grained substrate suitable for egg hatching. In this paper we use the results from a preliminary set of 2D computational simulations of flow within the 18-kilometer Critical Habitat reach to gain insight into the hydraulic cues the fish might use for spawning and the affect of flow management (Kootenay Lake Stage and Libby Dam discharge) on those cues. In addition we also use some very simple sediment transport simulations to gain insight into the role of pre- and post-dam flows in regulating the nature of the sediment substrate in the existing spawning reach.

BACKGROUND

Physical Setting: The Kootenai River originates in Kootenay National Park, British Columbia, Canada, and flows south into Montana and Lake Kookanuska formed by Libby Dam (Figure 1a). The river then flows east into northern Idaho and back north into British Columbia and Lake Kootenay. Bonnington Falls is between the confluence with the Columbia River and Lake Kootenay and provides natural barrier to fish migration that has isolated the Kootenai River white sturgeon from the rest of the Columbia River basin since the last glacial period approximately 10,000 years ago (Duke and others, 1999).

Geomorphology: The reach of interest to this study can be separated into three different geomorphic reaches including: a 16-rkm low-gradient, sandy, deep, and gently meandering reach downstream from Bonners Ferry, Idaho (rkm 244-228); a 10-rkm, high-gradient, gravel-cobble, shallow and braided reach upstream from Bonners Ferry (rkm 258-246); and a 2-rkm straight transition reach of high gradient and mixed sand and gravel substrate (rkm 246-244) (Figure 1b).



(modified from, Barton and others, in press)

Figure 1. (A) General location of study area and (B) detail location of study reach and Critical Habitat reach.

The river gradient changes dramatically in the transition reach from about 0.0006 in the braided reach to 0.00002 in the meandering reach. In addition, Kootenay lake levels vary from approximately 532-539 meters above the North American Vertical Datum of 1988 (NAVD88), in the pre-dam era to 532-535 meters in the post-dam era. These lake levels intersect the Kootenai River longitudinal profile between the upstream end of the meandering reach and into the braided reach. Consequently, the meandering reach is entirely in backwater. The backwater transition zone (Berenbrock and Bennett, 2005a) identifies the region of transition between free-flowing and backwater flow conditions over the range of potential discharge and Kootenay Lake stage conditions (Figure 2). Both the local gradient of the river and the backwater conditions lead to sharp change in hydraulic characteristics between the meandering and braided reach. Based on 1D model simulations, cross-sectional average velocities range from 0.25 – 1.0 and 0.75 – 2.0 meters per second and average depths range from 5 – 10 and 2 – 5 meters in the meandering and braided reaches respectively over a range of flows from 170 – 2125 cubic meters per second (Berenbrock, 2005b). In general, the meandering reach is twice as deep and half as fast as the braided reach.

Spawning Habitat: To document the timing and location of spawning events, artificial substrate mats were placed on the bed of the river during the period 1994-2002 (Paragamian and others, 2001 and Paragamian pers. com., 2004). Figure 3 shows the cumulative effort, reported as the number of hours the egg mats were deployed at each monitoring location, the number of spawning events, and the spawning events per unit of effort (SEPUE), which is the number of spawning events normalized by the cumulative effort. A spawning event simply represents the presence of eggs at the specific location. Eggs found on the substrate mats were aged to identify the potential presence of multiple spawning events. Several distinct groupings of spawning locations are noticeable and are broadly associated with the outside of meander bends (Figure 4).

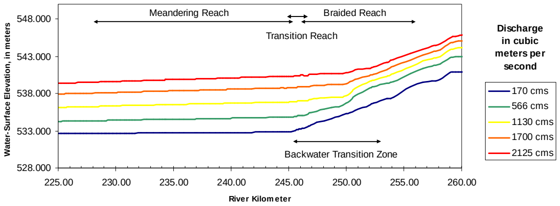


Figure 2. Simulated water-surface elevations in the study area from a 1-Dimensional flow model from Berenbrock (2005b).

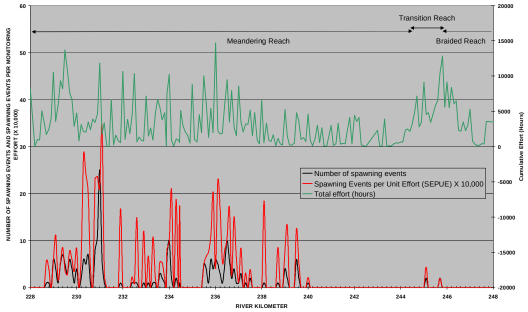


Figure 3. Location and magnitude of spawning events in the study reach

Studies of sturgeon spawning habitat in other river basins in the western United States where spawning and rearing are successful, including the Sacramento River, the Columbia River, and the Fraser River, generally describe the location of spawning sites as having relatively high velocity and a substrate that is composed of gravel and larger-sized material (Paragamian and others, 2001; Perrin and others, 2000; and Parsley and others, 1993). However, there are some site-specific differences from these idealized habitat values. Spawning sites on both the Sacramento and Fraser Rivers are associated with some sand as well as coarser material and on the Fraser River generally are located in shallower water. As previously noted, spawning sites in the Kootenai River are located in lower velocity compared to other rivers and are predominantly over sand-sized material. In all systems spawning tends to occur near the peak or descending limb of the hydrograph.

In this study we will address the paradox between the current (2005) spawning locations in the Kootenai River, even though there is a region of what appears to be a more suitable habitat for spawning in terms of higher velocity and coarser substrate a few kilometers upstream.

Channel Substrate: Several studies have been conducted to characterize the channel substrate in Kootenai River in the existing spawning reach. Barton (2004) used vibra- and piston-cores collected uniformly through the length of the Critical Habitat reach. Based on the grain-size and stratigraphy of the these cores, the river was classified into three broad zones; a sand-gravel-cobble zone in the transition reach downstream from Bonners Ferry; a buried gravel-cobble zone between 241-244.5 rkm; and a sand zone with isolated lenses of buried cobble downstream from 241 rkm. A subsequent vibra-core study in 2004 to better characterize the stratigraphy of the buried grave-cobble zone for 1D-sediment transport modeling (Berenbrock, 2005b) found that this zone is characterized by smaller lenses of buried coarse material. Figure 5 shows the locations of cores containing gravel or cobble sized material for the two studies above.

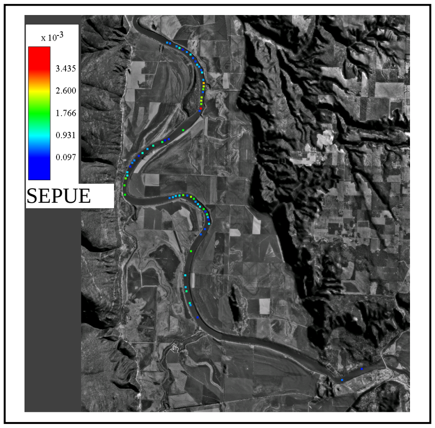


Figure 4. Spatial location of spawning events

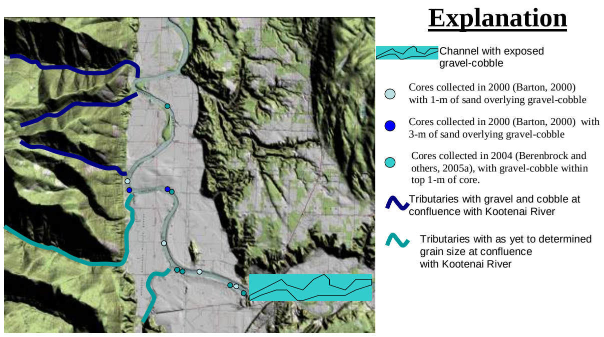


Figure 5. Location of gravel and cobble within existing spawning reach

In addition to the coring studies, informal field observations have identified that gravel-cobble sized material occurs at the confluence of three small tributaries with the Kootenai River in the downstream region of the study area (Figure 5). Presumably, periodic large floods would provide a limited supply of coarse material from these small tributaries to the river. The two larger tributaries, Deep Creek and Myrtle Creek (Figure 1), have gravel-cobble size material in their upper reaches. However, their potential for delivering coarse material to the river is yet to be determined, particularly as both travel significant distances over the broad and relatively flat floodplain, and are backwatered by the river itself before their confluence with the Kootenai River. Clearly, the gravel-cobble substrate within both the transition and braided reaches provide a potential source of coarse material to the meandering reach. Of 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.

2-DIMENSIONAL FLOW MODEL

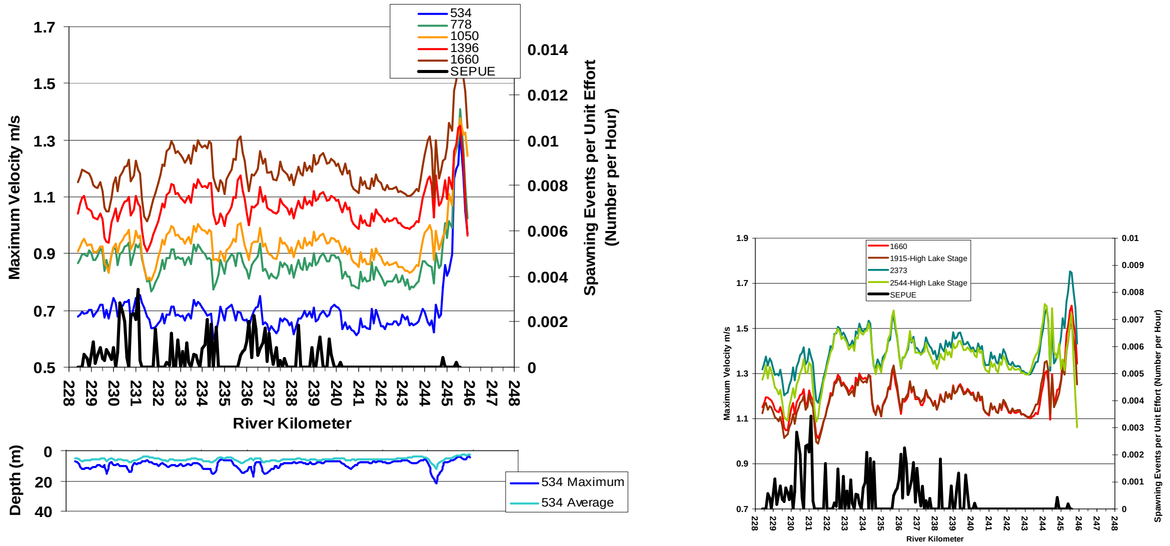
The USGS multidimensional surface-water modeling system (MD_SWMS) was used to simulate water-surface elevation, velocity, and boundary (bed) shear stress throughout the 18-rkm Critical Habitat reach (figure 1b). Subsidiary methods are used to simulate both the motion of sediment and morphologic evolution of the riverbed. MD_SWMS is a Graphical User Interface (GUI) developed by the USGS (McDonald and others, in press) for hydrodynamic models. FaSTMECH is one computational model within MD_SWMS and was developed at the USGS (Nelson and others, 2003). FaSTMECH includes a 2-dimensional, vertically averaged model and a sub-model that calculates vertical distribution of the primary velocity and the secondary flow about the vertically averaged flow. This so-called 2.5-dimensional approach has been shown to adequately simulate the velocity field, bed shear stress, and resulting patterns of erosion and deposition where secondary flows are significant, such as meander bends, without the complexity of a fully 3-dimensional model. Details of the model development, calibration and verification for the Kootenai River can be found in Barton and others (in press) .

MODEL SIMULATIONS OF VELOCITY AND DEPTH AND THE SPATIAL CORRELATION WITH SPAWNING LOCATIONS

As previously stated, one of the goals of this study is to look at the potential hydraulic cues the sturgeon are keying on for spawning site selection. A conceptual model of sturgeon spawning behavior based on hydraulic parameters in the current spawning reach might also lead to a better understanding of why sturgeon do not appear to spawn further upstream in the braided reach.

Typically, models of spawning habitat are developed based on the suitability of velocity and depth in terms of hydraulics and grainsize in terms of substrate (Parsley and others, 1993). For example, spawning suitability is generally described in terms of a range of desired magnitude for velocity or depth from values measured near the time of spawning at egg-collection locations. Spawning in any river basin typically occurs over a range of discharges, so the suitability of velocity developed in this way often reflects a wide range in velocity that to some degree simply reflects the range of discharge. The advantage of using a spatially distributed model such as the one used here is the entire river can be simulated at any particular point in time. Thus when looking at the suitability of spawning habitat based on velocity, the spatial distribution of velocity throughout the river for the discharge at the time of spawning is used rather than a range of velocity magnitude measured at various points in space and time in which discharge may substantially vary.

Model Results: Spawning in the Kootenai River during the time period 1994-2002 occurred over a range of discharges between approximately 500 – 1500 cubic meters per second (cms). To compare model simulations of depth and velocity over a similar range we picked five periods of time from the historical record where the discharge was both relatively constant for 2 or more days and fell within the range of 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 maximum velocity for each of the five discharges is shown in Figure 6A along with the SEPUE and the average and maximum depth for the lowest discharge.



A

B

Figure 6. (A) Model results of maximum cross-sectional velocity every 0.1 rkm at five discharges (the number in the explanation of each graph corresponds to the discharge value) which span the range of discharge during spawning are shown along with SEPUE. The maximum and average depth at each cross-section also is shown. (B) Model results of maximum cross-sectional velocity for simulation of discharges near the pre-dam mean annual peak flow of 2200 cubic meters per second at both high (labeled) and low Kootenay Lake stages.

Hydraulic and Habitat Spatial Correlations: Qualitatively (Figure 6A) there appears to be a positive correlation between spawning location and both high maximum velocity and high maximum depth. To test this observation we performed a spatial correlation between spawning location and maximum velocity and maximum depth by shifting velocity and depth each over a 1.0 rkm range both upstream and downstream by 0.1 rkm increments (Figure 7). The resulting correlations, reported as R^2 values and with significance at the 99th percentile, while not particularly robust show broad regions of positive correlation centered on the position of maximum velocity and depth. In addition, the correlations fall 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 sturgeon are keying in on regions of highest velocity and greatest depth. This relationship has been presented in many other studies of sturgeon spawning habitat. However, in this study we present a slight modification by suggesting that there is not a particular threshold velocity or even a specific range of velocity sturgeon key on, rather, all other things considered such as sufficient discharge and temperature, they appear to key in on the highest velocity and depth within the spawning region for the given discharge that is occurring when the fish are physiologically ready to spawn. This apparent behavior suggests that fish, when ready to spawn, will seek out the best perceived location to deposit eggs given the current environmental conditions. Under current flow conditions the sturgeon must move through many of these high velocity or high depth regions before entering the braided reach.

Figure 6B shows simulated maximum velocity for four modeled discharges (values reported in figure explanation) which represent a range of flows close to the pre-dam mean annual peak flow (2200 cms) with both pre-dam high and low Kootenay Lake stages. Prior to this study it has been hypothesized that higher pre-dam Kootenay Lake stages damped velocities in the meandering reach and encouraged sturgeon to move into the braided reach. The limited number of simulations performed in this study shows that while the velocity may be slightly reduced in the meandering reach under higher lake stages compared to lower lake stages, the variability in velocity remains. However another interesting pattern emerges from the simulations; the maximum velocity in the meandering reach under the highest flows approach that of the maximum velocity in the transition reach thereby reducing the velocity contrast that exists between the two reaches at lower flows. This reduction in velocity contrast is enhanced under higher Kootenay Lake stages. Perhaps the additive affect of high discharge and high lake levels reducing the velocity contrast in the transition reach rather than reducing the velocity in the current spawning reach encouraged the fish to move up into the braided reach during pre-dam flow conditions where there was extensive suitable substrate.

Discussion of Modeling Results: Paragamian and others (2002) reported on the movement of reproductively mature Kootenai River white sturgeon from staging reaches between 203 - 216 rkm to the Critical Habitat reach (228 – 246 rkm) in the spring, within one to two weeks from the onset of spring high runoff and rising water temperatures. During the period 1994 – 1999, no tagged sturgeon were recorded upstream from Bonners Ferry in the braided reach. If the sturgeon are indeed keying on regions of high velocity, then as they move into and through the current spawning reach there are numerous potential spawning locations all of which appear to be used. In addition, at the lower flows there is a sharp velocity contrast at the boundary of the meandering reach with the transition reach and at all flows the maximum velocity is significantly higher in the transition reach. Perhaps the combination of several potential spawning locations and the sharp change in velocity at the transition zone prevent the sturgeon from moving further into the braided reach. Here our discussion is limited to the river hydraulics, however other biologic factors such as photophobia, which, with severely reduced turbidities and lighted bridges and buildings, may preclude sturgeons from migrating into the relatively shallow braided reach (M. J. Parsley, written communication, 2005).

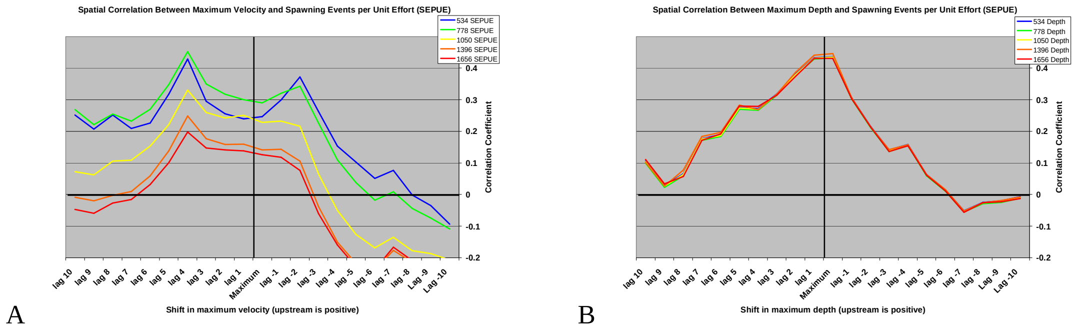


Figure 7. (A) the spatial correlation between streamwise maximum velocity and SEPUE, and (B) the spatial correlation between streamwise maximum depth and SEPUE. The lag is the shift in the velocity or depth profile respectively at 0.1 rkm increments (positive is upstream).

The results of our analysis suggest that sturgeon are spawning in the existing reach due to available habitat in the form of high velocity and depth over a range of flows. The affect of relatively high backwater conditions on velocity and depth is small, resulting in slight decreases and increases in the magnitude of velocity and depth respectively, but the spatial variability, which appears to be important based on the analysis presented here, remains intact. A possible hydraulic explanation to the lack of sturgeon spawning in the braided reach is the high velocity contrast at the boundary between the meandering reach and the braided reach. The affect of higher pre-dam discharges and Kootenay Lake levels is a damping of this contrast which may have lead spawning sturgeon to migrate up into the braided reach.

SEDIMENT TRANSPORT SIMULATIONS

The only year with measurable survival to the juvenile stage for Kootenai River white sturgeon during the post-dam period was 1974. Uniquely this year had both high discharge (~1300 cms) and relatively long duration (14 days) compared to any other year in the post-dam record (Figure 8A). Both 1991 and 1997 (Figure 8B) showed signs of some limited but unsuccessful recruitment (Duke and others, 1999). Flow regulation has long been postulated as a potential player in the lack of successful recruitment by decreasing the transport of fine-grain sand in the system and leaving potential coarse material buried. As noted previously, there are sources of suitable substrate identified in the Critical Habitat reach but most if not all is buried to some degree by sand. To explore the potential of high flows to periodically remove the sand and expose coarse gravel or a suitable substrate for egg adhesion we used the 1974 hydrograph as a test case in a sediment-transport simulation. We idealized the hydrograph to a steady-flow period of 14 days at a constant discharge of 1300 cms, 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 Critical Habitat reach.

Sediment-Transport Model: Details of the sediment transport model can be found in Nelson and others (2003). We note here several of the specific assumptions used in the model; the transport was assumed to be in equilibrium with the bed, a mean grain-size (0.2 mm) equivalent to the existing bed was used, only a single grain-size is considered, and we used the Engelund - Hansen total load equation to determine the transport rate.

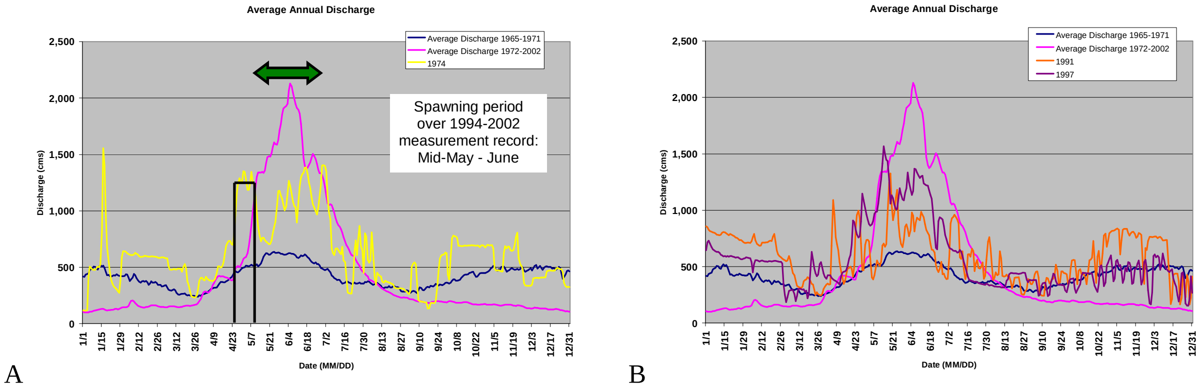


Figure 8. (A) Average discharge during the pre-dam period from 1965-1971, post dam conditions from 1972 – 2002, and 1974 hydrograph; the only year of successful recruitment in the post-dam period. The rectangular bracket shows the period and magnitude of the sediment-transport simulation. The green arrow represents the measured spawning period. (B) Avearage discharge for 1991 and 1997 each with limited recruitment.

Sediment-Transport Model Simulation: Figure 9 A-C shows the beginning, ending, and change in topography respectively for a small reach of meandering river at 234-235 rkm. This reach lies within the historically active spawning reach. Note that there is generalized scour of approximately 1 meter as shown by the negative change in elevation on Figure 9C throughout the outside of the meander bend and more locally extensive scour of up to approximately 3 meters near the apex of the meander bend. Based on the core records as shown in Figure 5 the scour would be sufficient to at least partially expose some buried gravel and cobble.

These results should be viewed with some degree of caution. While we have relatively good confidence in the pattern of scour and deposition as shown in Figure 9C, the magnitude of the change is much less certain for several reasons. As stated earlier the 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 and we started with the topography as measured at a specific point in time. The results clearly indicate the potential for flow with magnitude and duration as that in 1974 to scour the bed and expose limited patches of suitable substrate.

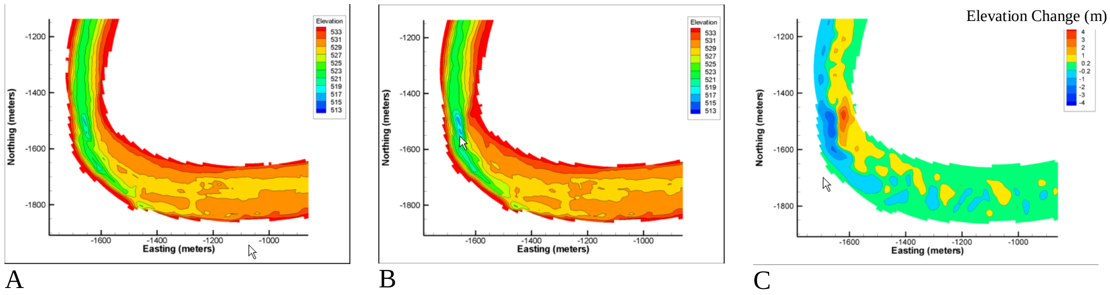


Figure 9. (A) Beginning topography, (B) ending topography and (C) change in topography for the 2-dimensional sediment transport simulation with constant magnitude of 1300 cms and duration of 14 days.

SUMMARY

Why Kootenai River white sturgeon do not spawn in the braided reach remains an open question. Based on the analysis presented here we identified that a velocity contrast exists between the relatively high velocity braided reach and the low velocity meandering reach. At the highest discharges associated with pre-dam peak flows, the difference between the existing post-dam managed flow regime and the natural pre-dam flow regime may have encouraged the white sturgeon to migrate further upstream and spawn over suitable substrate. Unfortunately, there is no historical evidence to show whether or not white sturgeon ever spawned within this reach. However, there is evidence that white sturgeon occupied areas within the braided reach, therefore spawning may have occurred here.

Our study adds to the understanding of spawning site selection in the current spawning reach. The sturgeon appear to seek the highest velocity and depth regions within the meandering reach to spawn as indicated by the spatial correlation analysis. The spatial location of these regions remains relatively constant at all flows though the region with highest velocity changes depending on the discharge. In the post-dam period most of the channel substrate in the spawning reach is composed of sand and despite the current levels of spawning, the sandy substrate likely remains a major bottleneck by increasing mortality of eggs which may require a coarser substrate to successfully incubate.

Paragamian and others (2001) noted that the Kootenai River white sturgeon use a longer reach of river to spawn than white sturgeon elsewhere. Perhaps this is an adaptation to 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 and 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. Metapopulation theory suggests that dispersal of progeny over large areas has adaptive value to long-term persistence of populations. It is possible that the Kootenai River population of white sturgeon, once they became geographically isolated, adapted a strategy of spawning widely over marginally suitable habitats. However, human development within the Kootenai River basin has degraded these habitats. Although historically these areas may have been marginally suitable for spawning and egg incubation, they no longer are capable of providing all the requirements leading to successful hatching and production of enough free-swimming embryos to sustain the population.

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