Modeling the Effect of Flow and Sediment Transport on White Sturgeon Spawning Habitat in the Kootenai River, Idaho

Richard McDonald[1]; Jonathan Nelson, M.ASCE[2]; Vaughn Paragamian[3]; and Gary Barton[4]

Abstract: Kootenai River white sturgeon spawn in an 18-km reach of the Kootenai River, Id. Since completion of Libby Dam upstream from the spawning reach in 1972, 1974 is the only year with documented significant 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 (2008) 18-km spawning reach is composed primarily of sand and some buried gravel; within a few kilometers upstream there is an extended reach of clean gravel, cobble, and bedrock. We used a quasi-three-dimensional flow and sediment-transport model along with the locations of collected sturgeon eggs as a proxy for spawning location from 1994 to 2002 to gain insight into spawning-habitat selection in a reach which is currently unsuitable due to the lack of coarse substrate. Spatial correlations between spawning locations and simulated velocity and depth indicate fish select regions of higher velocity and greater depth within any river cross section to spawn. These regions of high velocity and depth occur in the same locations regardless of the discharge magnitude as modeled over a range of pre- and postdam flow conditions. A flow and sediment-transport simulation shows high discharge, and relatively long-duration flow associated with predam flow events is sufficient to scour the fine sediment overburden, periodically exposing existing lenses of gravel and cobble as lag deposits in the current spawning reach. This is corroborated by video observations of bed surface material following a significant flood event in 2006, which show gravel and cobble present in many locations in the current spawning reach. Thus, both modeling and observations suggest that the relative rarity of extremely high flows in the current regulated flow regime is at least partly responsible for the lack of successful spawning; in the predam flow regime, frequent high flows removed the fine sediment overburden, unveiling coarse material and providing suitable substrate in the current spawning reach.

DOI: 10.1061/(ASCE)HY.1943-7900.0000283

CE Database subject headings: River systems; Velocity; Depth; Shear stress; Sediment transport; Sand, hydraulic; Gravel; Scour; Dams; Ecosystems; Idaho.

Author keywords: River systems; Velocity; Depth; Shear stress; Sediment transport; Sand; Gravel; Scour; Dams; Ecology.

Introduction

The Kootenai River white sturgeon population is physically isolated and genetically distinct from other white sturgeon populations in the Columbia River basin (Setter and Brannon 1990). Following the completion of Libby Dam by the U.S. Army Corps of Engineers in Montana during 1972, the only year of relevant recruitment to the population occurred in 1974 (Paragamian et al. 2005). During subsequent years, a small number of naturally produced juvenile fish have been found but their abundance is too low to sustain the population (Paragamian et al. 2005; Paragamian and Hansen 2008). In 1994 the Kootenai River white sturgeon population was listed as endangered [U.S. Fish and Wildlife Service (USFWS) 1994]. Further protection was obtained in 2001 through the designation of 18 river kilometers (rkm) downstream from Bonners Ferry, Id., as critical habitat [U.S. Fish and Wildlife Service (USFWS) 2001]. Increased spring flows from Libby Dam for spawning in recent years appear to have resulted in increased spawning as evidenced by the collection of more sturgeon eggs (Paragamian et al. 2002). Monitoring locations of adult white sturgeon through telemetry studies and inferring general spawning locations from egg collections has consistently shown the critical habitat reach to be the main region of spawning (Paragamian et al. 2001).

White sturgeon are broadcast spawners with eggs that become adhesive shortly after exposure to water (Scott and Crossman 1973; Conte et al. 1988). Where successful spawning occurs in other river systems, eggs are assumed to settle into interstitial spaces provided by coarse substrates such as gravels and cobbles (Parsley et al. 1993; 2002). Successful spawning of Kootenai River white sturgeon occurs annually from approximately mid-May to June within the critical habitat reach, confirmed by the annual presence of viable eggs and developing embryos (Paragamian et al. 2001). However, the river substrate under most flow

[1]Hydrologist, Geomorphology and Sediment Transport Laboratory, USGS, 4620 Technology Dr., Suite 400, Golden, CO 80403 (corresponding author). E-mail: rmcd@usgs.gov

[2]Hydrologist, Geomorphology and Sediment Transport Laboratory, USGS, 4620 Technology Dr., Suite 400, Golden, CO 80403. E-mail: jmn@usgs.gov

[3]Biologist, Idaho Dept. of Fish and Game, Coeur D'Alene, ID 83815. E-mail: vaughn.paragamian@idfg.idaho.gov

[4]Hydrogeologist, Idaho Water Science Center, USGS, Boise, ID 83702. E-mail: gbarton@usgs.gov

Note. This manuscript was submitted on February 4, 2009; approved on May 18, 2010; published online on May 19, 2010. Discussion period open until May 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 136, No. 12, December 1, 2010. ©ASCE, ISSN 0733-9429/2010/12-1077–1092/$25.00.

conditions in the critical habitat reach is predominantly composed of fine sand with large migrating dunes (Barton 2004). Spawned eggs are presumed to settle onto the bed and may become covered in fine sand or buried in the trough of migrating dunes resulting in suffocation and/or predation. As little as 5 mm of fine sediment cover can cause up to 100% mortality to incubating white sturgeon embryos (Kock et al. 2006). Interestingly, a few kilometers upstream from the spawning locations, the river has suitable substrate composed mostly of gravel and cobble; however, the channel changes from a meandering form to a braided form that is relatively shallow and fast compared to the meandering reach.

Successful spawning and recruitment of Kootenai River white sturgeon involve complicated biological and ecological processes that may be affected by hydraulic and sediment-transport characteristics. The reason that Kootenai River white sturgeon select their current spawning grounds is not known. It may be an evolutionary artifact from over 10,000 years of spawning in the present reach of river. Alternatively, they may be compelled to spawn there because preferred habitat is unavailable or false environmental cues are present. Several hypotheses relating to the hydraulic and sediment-transport characteristics of the Kootenai River have been put forth as possible explanations for the decline of successful recruitment in this system. Duke et al. (1999) outlined how Libby Dam may have affected successful sturgeon spawning. First, prior to Libby Dam, higher lake stage in Kootenay Lake resulted in greater backwater extent, increasing river stage, which may have encouraged the fish to spawn further upstream in the braided reach. Second, in the postdam period, the loss of naturally occurring high spring flow in addition to lower Kootenay Lake stages may have shifted the spawning further downstream into the current spawning reach. Third, the higher predam discharge may have mobilized and scoured the bed sufficiently in the current spawning reach to expose coarse-grained substrate suitable for egg hatching.

The goal of this paper is to examine the hydraulic and sediment-transport hypothesis presented by Duke et al. (1999) using field observations and the results of a coupled flow and sediment-transport model encompassing the 18-km critical habitat reach to (1) gain insight into the hydraulic conditions in the spawning reach; (2) assess whether these hydraulic conditions serve as spawning cues; (3) assess the effects of flow management (Kootenay Lake Stage and Libby Dam discharge) on those cues; and (4) gain insight into the role of pre- and postdam flows in regulating the sediment substrate characteristics in the spawning reach.

Background

Natural climate variability in the Pacific Northwest during the Pleistoscene and Holocene produced a diverse landscape shaped to a large degree by the advance and retreat of the continental ice cap. Glacial land forms, including lacustrine, fluvial, and moraine deposits, influence the local hydraulic conditions and nature of the bed material in the study area. More recently, the Kootenai River basin has undergone dramatic changes in land use and management of the river for flood control and hydroelectric generation; these actions also have a substantive effect on the hydraulics of the river. Natural recruitment of juvenile sturgeon has been in decline since the 1950s (Paragamian et al. 2005) with inconsistent recruitment of sturgeon during the 1960s, followed by an almost total lack of natural recruitment during the period of flow management through Libby Dam from 1975 to the present. For these

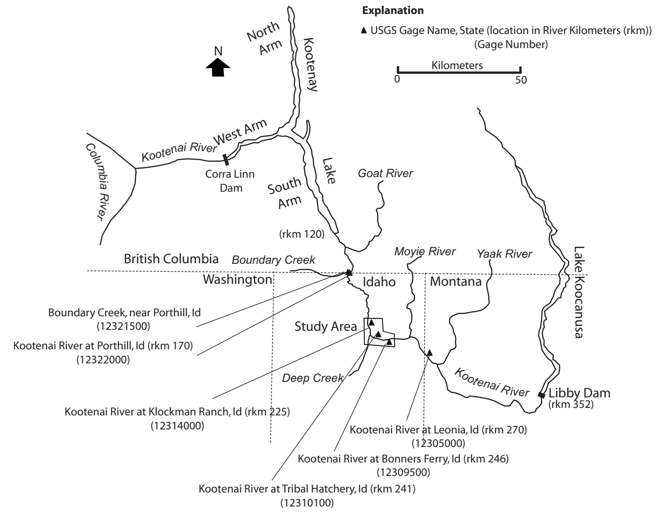

Fig. 1. Location of study area near Bonners Ferry, Id.

reasons, a brief overview of the geomorphology, hydrology, and white sturgeon biology is given to provide the proper context for the study presented here.

Geomorphology

The Kootenai River is 721 km long and a major tributary to the Columbia River (Fig. 1). The Kootenai River originates in Kootenay National Park (spelled Kootenay for Canadian waters), B.C., Canada, and flows south into Montana and Koocanusa Reservoir formed by Libby Dam. Below Libby Dam the river flows generally to the west through bedrock canyons and into northern Idaho near the town of Bonners Ferry. For the 11-km reach upstream from Bonners Ferry, the channel is unconfined and weakly braided as it exits the bedrock canyon reach. Downstream from Bonners Ferry the river meanders north for 85 km back into British Columbia and the south arm of Kootenay Lake.

Three geomorphic reaches have been identified in the study reach—a canyon reach, a braided reach, and a meander reach (Snyder and Minshall 1996). The canyon reach extends from Libby Dam to the Moyie River confluence (Figs. 1 and 2) where the valley begins to widen (rkm 365.7–256.6). The braided reach extends to the bedrock constriction at Ambush Rock near Bonners Ferry (rkm 256.6–245.9). The braided reach has since been subdivided by breaking out the short straight reach between rkm 245.9 and 244.5 and identifying a transition zone between the meandering reach and the braided reach (Barton 2004) hereafter referred to as the transition reach. The meander reach extends downstream from the bedrock constriction (rkm 244.5) near Bonners Ferry for approximately 100 km to Lake Kootenay. The 18-km (rkm 228–246) reach of critical habitat (hereafter referred to as the critical habitat reach) extends downstream from Bonners Ferry and includes the transition reach and the top 16.5 rkm of the meandering reach

The braided reach has a slope of approximately 0.00046 and lies in a wide and flat valley bounded by thick glaciolacustrine and glaciofluvial terraces (Weisel 1980). The reach consists of multiple channels that are actively migrating. At the transition reach (near Bonners Ferry) the width of the valley floor narrows again and contains numerous bedrock outcroppings. Depths in the braided and transition reach are approximately 1–3 m and the bed material is generally gravel and cobbles with some sand in the

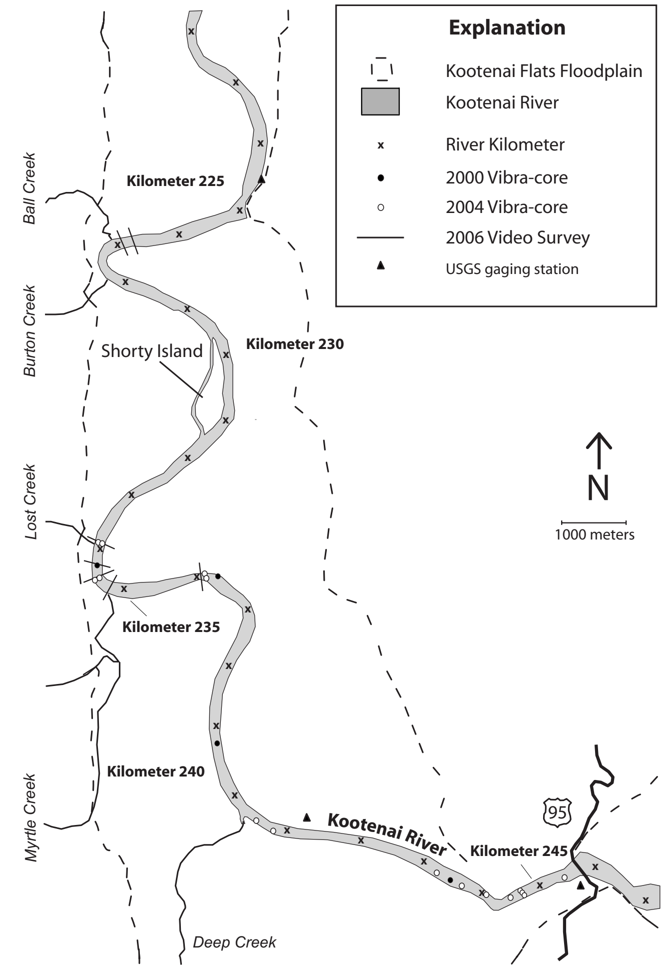

Fig. 2. Map view of the study area showing the Kootenai River and location of cores collected during sampling in 2000 (Barton 2004) and 2004 (Berenbrock and Bennett 2005) that contained or indicated gravel or cobble material. Minor tributaries, which may be a local source of gravel or coarser material to the current spawning reach, are identified as well as the location of video cross sections surveyed in 2006. The 18-km critical habitat reach as defined by the U.S. Fish and Wildlife Service (USFWS) (2001) is contained within the meandering reach between rkm 228 and 246. The braided reach is upstream from rkm 246.

transition reach. The meander reach has a gentle slope of 0.000 02 and meanders across lacustrine deposits filling the wide valley bottom in the Kootenai Flats floodplain. The Boundary County Soil Survey (USDA 2007) maps the soils on the valley bottom as primarily glacially derived lacustrine with some interbedded fluvial deposits. The bed material consists of predominantly sand deposits and discrete interbedded gravels and cobbles with some lacustrine clay steps, particularly in the lower part of the reach near Shorty Island. Large dunes migrate along the bottom during low flow and are washed out at higher flows.

Hydrology

The present flow regime as managed by releases from Libby Dam is quite different from the natural flow regime. Libby Dam was completed in 1972 and became fully operational in 1974. Average annual Kootenai River discharge is shown in Fig. 3(a) during 1966–1971 prior to emplacement of Libby Dam, 1972–1990 during the post-Libby Dam era, and 1991–2002 during the period of experimental flow modification. During the predam period from 1966 to 1971, the annual average peak flow occurred in mid-June and was approximately 2,200 m^3/s. In contrast, during the postdam period from 1971 to 1990 the annual average peak flow was approximately 600 m^3/s; this represents a 72% reduction in predam average peak flow. A period of experimental flows occurred from 1991 to 1994 to aid recruitment and to monitor the response of the Kootenai River white sturgeon (Duke et al. 1999). These experimental flows were further modified in 1995 and in subsequent years according to the Biological Opinion [U.S. Fish and Wildlife Service (USFWS) 2000] in response to the listing of the Kootenai River white sturgeon as an endangered species in 1994. The annual average peak flow during the period from 1991 to 2002 was approximately 750 m^3/s or slightly larger than that during the postdam period prior to flow modification.

The average annual hydrograph provides a good baseline indication of the flow magnitude and duration during the year; however, the actual flow during any individual year exhibits substantial variability about the mean [Figs. 3(b–d)]. The natural variability of flow is thought to be key to health of a river ecosystem, where all aspects of the flow variability from seasonal high and low flows as well as intraseasonal pulses of high flow and interannual variability of extreme flows are linked to a variety of ecological needs, each contributing to the health of a river ecosystem (Richter et al. 1996; Poff et al. 1997). During the predam unregulated flow regime from 1966 to 1971 [Fig. 3(b)], the hydrograph began rising rapidly near the beginning of May with flow at or exceeding 2,000 m^3/s by the middle of May. In these years during the predam era, the flow exhibited large variations in flow magnitude during the sturgeon spawning season through May and June. During the postdam period [Figs. 3(c and d)] with few exceptions, the flow magnitude was much lower preceding and through the spawning season than in the predam period, and the variability of the flow during the spawning season was generally lower in magnitude and shorter in duration than during the predam period. The importance of the natural flow variability during the spawning season for conditioning the channel bottom substrate by winnowing the fines and exposing coarse gravel lag deposits prior to sturgeon spawning will be discussed below.

The backwater transition zone (Berenbrock 2005) identifies the region of transition between free-flowing and backwater flow conditions over the range of potential discharge and Kootenay Lake stage conditions. Kootenay Lake levels vary from approximately 532 to 539 m above the North American Vertical Datum of 1988 in the predam era to 532–535 m in the postdam era. These lake levels intersect the Kootenai River longitudinal profile between the upstream end of the meandering reach and the lower 2–3 km of the braided reach. Consequently, the meandering reach is entirely in backwater. Both the local gradient of the river and the backwater conditions lead to sharp change in hydraulic characteristics between the meandering and braided reaches. Based on one-dimensional (1D) model simulations, cross-sectional average velocities range from 0.25 to 1.0 and 0.75–2.0 m/s and average depths range from 5 to 10 and 2–5 m in the meandering and braided reaches, respectively, over a range of flows from 170 to 2,125 m^3/s (Berenbrock 2005, 2006). In general, the meandering reach is more than twice as deep and less than half as fast as the braided reach. As discussed below these differences in reach velocity and depth appear to play a role in spawning site location.

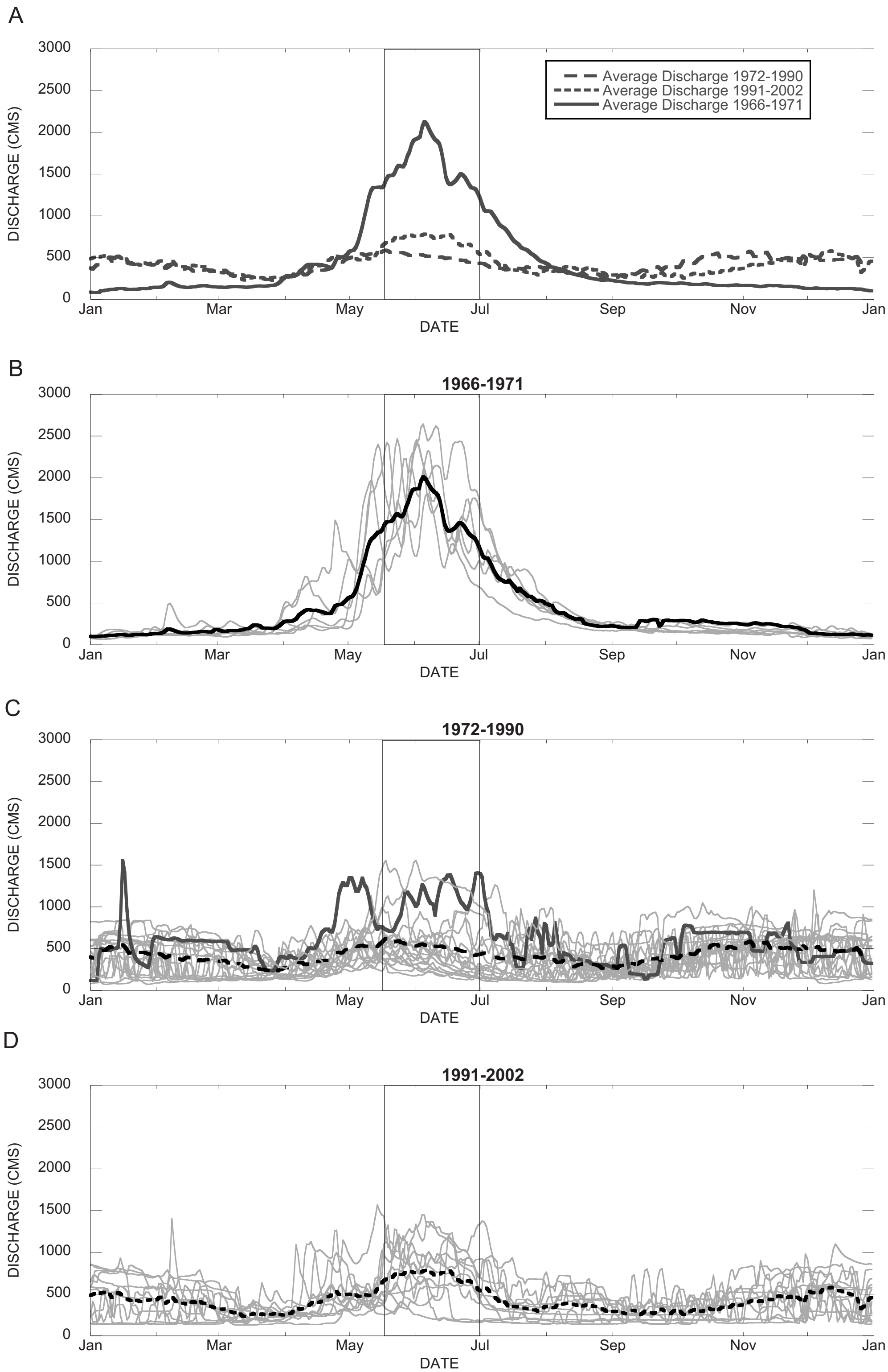

Fig. 3. Hydrographs including (a) average daily discharge for the periods 1965–1971 corresponding to the predam period, 1972–1990 corresponding to the postdam regulated discharge, and 1991–2002 corresponding to the postdam augmented flow for sturgeon studies. (b) Average daily discharge by year for the period 1966–1971. (c) Average daily discharge by year for the period 1972–1990. The year 1974 is represented by the bold dark gray line. (d) Average daily discharge by year for the period 1991–2002. In the plots (c) and (d), the average for the period is shown by the bold black line. It should be noted that while Libby Dam was competed in 1972, full management of flows did not occur until 1974. Discharge in all plots was calculated as the difference between the discharge at the USGS gauging station on Kootenai River at Porthill, Id. and the by the USGS gauging station located at Boundary Creek near Porthill, Id. Discharge data is from USGS National Water Information System (http://waterdata.usgs.gov/nwis). The black box bounds the typical annual spawning period.

White Sturgeon Biology

Studies of white sturgeon spawning habitat in other river basins in the western United States where spawning and rearing are successful, such as the Sacramento, the Columbia, and the Fraser rivers, generally describe the location of spawning sites as occurring in river reaches with relatively high velocity and a substrate that is composed of gravel and larger-sized material (Paragamian et al. 2001; Perrin et al. 2000, 2003; Parsley et al. 1993; Parsley and Beckman 1994; Coutant 2004; Golder Associates 2005). However, there are some site-specific differences from these idealized habitat values. Known spawning reaches 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 (Kohlhorst 1976; Schaffter 1997; Perrin et al. 2000, 2003). Conversely, known spawning sites within the critical habitat reach of the Kootenai River are located in lower velocity areas compared to other rivers and are dominated by sand-sized material during the current regulated flow conditions.

Kootenai River white sturgeons have reached critically low population sizes where genetic and demographic risks are significant. No relevant recruitment of juvenile sturgeon has occurred since possibly 1974 and consistent recruitment has not occurred since at least 1965. A few wild juveniles are periodically captured, but although recent managed flows (1991–present) have stimulated spawning, they have not apparently encouraged the survival of eggs and larva as hoped (Paragamian et al. 2001). Flow augmentation during spring may have stimulated sturgeon spawning behavior as eggs are collected in most years, but habitat changes and spawning locations are still unfavorable to egg survival (Paragamian et al. 2001; Anders et al. 2002). Consistent historic recruitment coincided with wet years and high runoff conditions that have been precluded by hydropower operations since completion of Libby Dam in 1972 (Paragamian et al. 2005). However, recruitment failures prior to Libby Dam construction suggest that early life history/recruitment has also been impacted by other habitat changes such as levee construction and disconnection from the river floodplain in the 1920s to the 1950s (Daley et al. 1981), Kootenay Lake regulation following the completion of Corra Linn Dam in 1932 (Duke et al. 1999), and changes in system productivity (Anders et al. 2002; Paragamian 2002).

Flow augmentation implemented to date has not increased the survival of eggs although measures have fallen short of targets desired by some fish managers (B. Hallock, U.S. Fish and Wildlife Service, personal communication). The key to designing such a restoration is how the fish select spawning sites and how the physical characteristics of those sites may be prohibiting the successful recruitment of juvenile fish from naturally spawned eggs. In the work described here, these issues are investigated using observed spawning sites along with the physical characteristics of the sites and computational flow modeling.

Field Data Collection

The channel topography, channel substrate, and white sturgeon egg-collection data used in this study were collected from several previous and ongoing studies as described below. The modeled reach of river extends from the upstream end of the critical habitat reach at Bonners Ferry (rkm 245.9) to 5.5 rkm downsteam from the critical habitat reach at rkm 222.5 (Fig. 2). The extent of the modeled reach was selected to provide insight to the hydraulic conditions of the critical habitat reach and conditions just downstream from the critical habitat reach to see what if anything is hydraulically unique about the reach.

Topography

Collecting channel bathymetry and bank and floodplain topography is the first step in characterizing the physical habitat and is required for computational models of flow and sediment transport. Bathymetry for the modeling reach is based on mapping conducted during 2002–2005. Details on the collection of bathymetric data are provided in Barton and Moran (2004) and Barton et al. (2005) and briefly summarized here.

Bathymetry was collected with real-time global positioning system (GPS) equipment interfaced with survey-grade single and multibeam echo sounders with a horizontal accuracy of ± 0.051 m and a vertical accuracy of ± 0.041 m (Barton and Moran 2004; Barton et al. 2005). During 2002 and 2003, 260 cross sections and two to seven longitudinal lines were surveyed in the modeling reach. Spacing between the cross sections ranged from less than 10 to about 50 m. During 2004 and 2005, topography was measured with a multibeam echo sounder. The spacing between each of the four sounding transducers was 2.8 m. Longitudinal lines were collected so they were roughly parallel and spaced relatively close to one another. The bank and floodplain topography was obtained from a light detection and ranging data set (Richard Duncan, GeoEngineers, personal communication, 2005) collected in 2005.

Channel Substrate

Several studies have been conducted to characterize the channel substrate in the Kootenai River in the existing spawning reach. Barton (2004) used vibracores and piston cores at various locations through the 18-km length of the critical habitat reach. Based on the grain size and stratigraphy of these cores, the river was classified into three broad zones: a sand-gravel-cobble zone in the transition reach downstream from Bonners Ferry (245.9–244.5 rkm), a buried gravel-cobble zone (244.5–241 rkm), and a sand zone with isolated lenses of buried cobble (241–228 rkm) (Fig. 2). A subsequent vibracore study in 2004 to better characterize the stratigraphy of the buried gravel-cobble zone for 1D sediment-transport modeling (Berenbrock 2005) found that this zone is characterized by discontinuous lenses of buried coarse material. Fig. 2 shows the locations of cores containing gravel or cobble sized material for the two studies above.

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 meandering reach: Lost Creek, Burton Creek, and Ball Creek (Fig. 2). Periodic large floods from these small tributaries provide a limited supply of coarse material to the river. Two larger tributaries, Deep Creek and Myrtle Creek (Fig. 2), have gravel-cobble size material in their upper reaches. However, their potential for delivering coarse material to the river is uncertain, particularly as both must travel significant distances over the broad and relatively flat floodplain and are backwatered by the river itself upstream from their confluence with the Kootenai River. Without major tributary supplies, the gravel-cobble substrate within the transition and braided reaches may have historically provided coarse material to the meandering reach. Determining the location and extent of gravels in the current spawning reach is critically important for evaluating the role of higher flows in uncovering areas of sufficient spatial extent for successful spawning habitat.

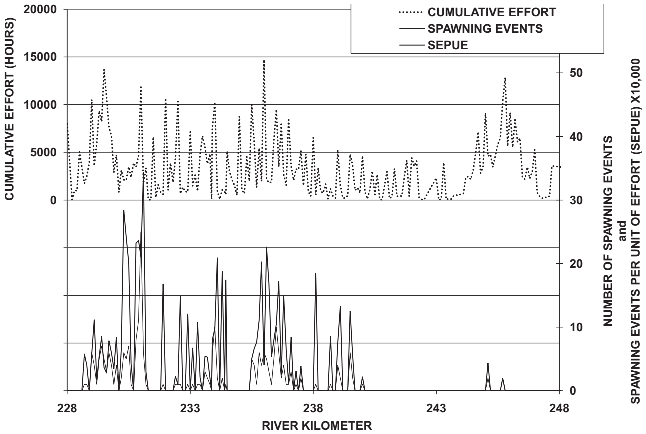

Fig. 4. Results of egg mat sampling from 1994 to 2002 at every 0.1 rkm in the Kootenai River presented as the number of spawning events (solid line), the SEPUE (short dashed line), and the cumulative level of effort (long and short dashed lines) at each sampling location

Egg Mat Studies

White sturgeon eggs were collected during rising, falling, and steady hydrographs in the Kootenai River between 1991 and 2002, though the most consistent period of egg collection was between 1994 and 2002. Eggs in the Kootenai River were sampled with 70–100 artificial substrate mats, hereafter referred to as "mats" (Paragamian et al. 2001), as described by McCabe and Beckman (1990). Several sampling schemes were implemented early in the spawning studies to help identify white sturgeon spawning locations, including deployment within staging reaches used prior to sturgeon spawning (Paragamian and Kruse 2001). In 1994 mats were set every 0.5 km from rkm 228 to 245.6. In 1995, they were distributed from rkm 215 to rkm 246 to sample a variety of habitats including three staging areas (Paragamian and Kruse 2001). In 1996, mats were distributed primarily in the thalweg from rkm 228 to 247.7 because no eggs were collected near the river margins in the previous 5 years of sampling (Paragamian et al. 2001). In 1997, mats were placed from rkm 227 to 247, and a standardized sampling regime was implemented thereafter based on the telemetry locations of adult white sturgeon: high (frequently located), medium (occasionally located), and low (seldom located) (Paragamian et al. 1997). Mats were usually set from early May to the first week in July after which they were pulled, examined for presence of eggs, and redeployed daily. Eggs were removed from mats and stored in labeled vials containing formalin or alcohol solution. The eggs were aged and spawning date was back-calculated from the collection date. The location and the number of spawning events at each 0.1-rkm sampling location are shown in Fig. 4. In addition, the cumulative effort (hours) at each sampling location is also shown. The spawning events per unit of effort (SEPUE) were calculated by normalizing the number of spawning events at each sampling location with the cumulative effort at that location. The SEPUE value provides a proxy indication of the strength of spawning as a function of rkm.

Flow and Sediment-Transport Modeling

The USGS Multidimensional Surface-Water Modeling System (MD_SWMS) was used to simulate water-surface elevation, velocity, and boundary (bed) shear stress throughout the 30-rkm critical habitat reach (Fig. 2). A sediment-transport model is used to simulate both the motion of sediment and morphologic evolution of the riverbed. MD_SWMS is a graphical user interface developed by the USGS (McDonald et al. 2005) for hydrodynamic models. FaSTMECH is one computational model within MD_SWMS and was developed at the USGS. A thorough description of the model can be found in Nelson and McDonald (1996) and Nelson et al. (2003). A brief introduction to FaSTMECH is described here to give context to its application herein. FaSTMECH includes two flow calculation components. The first component is a solution of the shallow water equations, with a closure for bed stress that incorporates a drag coefficient. The second component is a submodel that calculates the vertical distribution of the primary flow and the secondary flow about the streamlines of the vertically averaged flow. The full governing equations used in the computational solution are cast in a channel-fitted curvilinear coordinate system described in Nelson and Smith (1989). In the first part of the model, the shallow water equations are used to compute the vertical structure of flow along the vertically averaged streamlines as well as the cross streamline components of both the vertically average velocity and the bottom stress. Inputs to the vertically averaged model are discharge, topography, and roughness. The second part of the model computes the cross-stream components of velocity and Reynolds shear stress, yielding the vertical structure of secondary flows and the modification to the bottom stress associated with secondary flows. Inputs to the vertical-structure component of the model are eddy viscosity structure functions and the results of the vertically averaged model. The approach uses the assumptions that the flow is steady and hydrostatic, and the turbulence can be treated adequately by relating Reynolds stresses to flow shear using an isotropic eddy viscosity. This so-called quasi-three-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 three-dimensional model (Nelson et al. 2003).

The numerical solution technique employed in FaSTMECH solves the full vertically averaged equations on a curvilinear orthogonal grid using relatively standard methods. First, an explicit solution of the streamwise and cross-stream momentum equations is obtained for the vertically averaged velocity subject to a known (guessed) water-surface elevation and velocity fields. The initial guess is taken from a simple steady 1D flow solution. Second, the water-surface elevation is calculated using the semi-implicit method for linked equations (SIMPLE) (Pantankar 1980), which comprises an alternating-direction implicit scheme with operator splitting and a tridiagonal matrix solver. Water-surface elevation and velocity fields are updated in an iterative cycle using differential relaxation, and iteration continues until both mass and momentum conservation are satisfied to a high degree of accuracy at every point in the computational grid. Using solutions from the vertically averaged model, an assumed eddy viscosity structure from Rattray and Mitsuda (1974), and a spatial distribution of roughness lengths or drag coefficients, the vertical-structure component of the FaSTMECH model yields a full three-dimensional flow solution.

The model is applied to the entire study reach from rkm 222 to 246 which incorporates the critical spawning habitat. The model resolution is 10 m along the centerline of the grid, but varies slightly away from the centerline where the grid has curvature such as in meander bends. With this discretization there are gen-

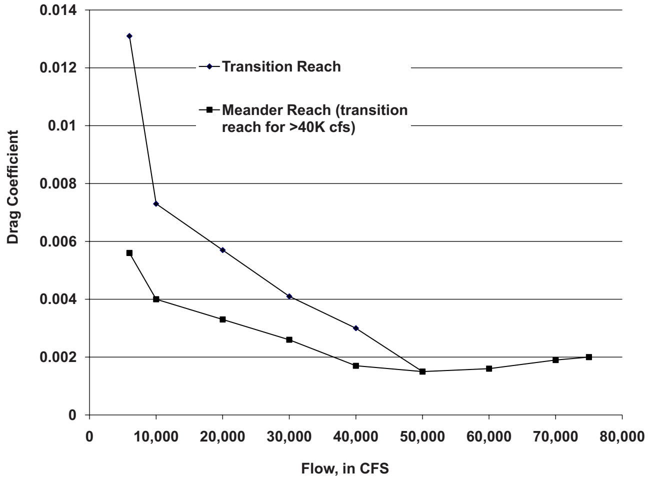

Fig. 5. Calibrated drag coefficients for both the transition and meandering reach as a function of discharge

erally 15–25 active computational grid nodes in the cross-stream direction. The model was calibrated to computed water-surface elevations, from a 1D model (Berenbrock 2005, 2006) that spans the study reach from rkm 170 to 276, from a wide selection of discharge magnitudes ($170–2,120\ m^3/s$) up to and exceeding the predam mean annual peak discharge. Complete details of the model calibration and verification for the Kootenai River can be found in Barton et al. (2005, 2009). A brief description of the calibration procedure and of the simulation verification as provided by a comparison between the simulated and measured velocities is provided here for completeness.

The model was calibrated with nine discharge conditions that ranged from 170 to $2,120\ m^3/s$. Water-surface elevations used to calibrate the model consisted of 37 points taken from the output of a 1D model (Berenbrock 2005, 2006) with an extent that spans the study reach from Leonia, Id. to Porthill, Id. The 1D model itself was calibrated to water-surface elevations recorded at the five historic and operating USGS gauges within and surrounding the study area (Fig. 1). The 1D model also provided the downstream water-surface elevation boundary condition. Model calibration consisted of comparing the differences between model simulated and the 1D model water-surface elevations and adjusting the roughness, which is specified as a drag coefficient to match 1D model water-surface profiles. Roughness in the model was partitioned according to the geomorphic reaches described earlier so that the transition reach (rkm 245.9–244.5) and meander reach (rkm 244.5–222) were each represented by a single value of drag coefficient. Physically, using a single value drag coefficient spatially is equivalent to assuming that the roughness length z_0 is inversely proportional to depth. The drag coefficient was adjusted such that the predicted water-surface elevation drop through each reach matched the results from the 1D model. Results of the calibration are shown in Fig. 5. The root-mean-square value of the water-surface calibration was between 0.015 and 0.025 m for all discharges. The calibrated drag coefficients decrease with increasing discharge up to approximately $1,500\ m^3/s$ after which they stay relatively constant. For the meander reach the drop in drag coefficient is attributed to a decrease in size of dunes with increasing discharge until the dunes wash out completely at about $1,500\ m^3/s$. A few observations of dune geometries were made at varying flows and show a decrease in dune amplitude and wavelength at higher flows. For the transition reach, where there is a lack of bed forms and drag is dominated by the relatively coarse gravel and cobble substrate, the drag decreases as the stage at higher discharges increases.

Measurements of velocity for model validation were obtained from an acoustic Doppler current profiler (ADCP) at 15 cross sections located throughout the study reach. Complete details of the validation can be found in Barton et al. (2005), and a brief summary is presented here. Velocities were measured during a period of relatively constant discharge of $538\ m^3/s$. To obtain velocity data suitable for comparison with a steady state model, 7–15 passes across the channel were measured with the ADCP at each cross section and then averaged in two ways, as documented in Dinehart and Burau (2005). First, vertically averaged velocities were obtained from each pass of the ADCP, and ensembles of vertically averaged velocities were created from all the 7–15 passes with the ADCP at each cross section and compared to model predicted vertically averaged velocities (Fig. 6). The model simulates both the magnitude and structure of flow across the section reasonably well, with a few notable exceptions. The model slightly underestimated the magnitude and location of peak velocities in cross sections at the apex of bends in the river, as in Sections 234.4 and 236.9 (Fig. 6). This is a common result for models that are not fully three dimensional and can be attributed to the lack of secondary flow feedback on primary velocity distribution. Second, the ADCP profiles of velocity were partitioned into streamwise and cross-stream components, and the 7–15 passes at each cross section were averaged and then compared to model results. An example is shown in Fig. 7. While 7–15 passes of the ADCP were still insufficient to generate good average velocity profiles suitable for comparison with a steady state model, the results are still in good agreement with the magnitude and structure of the flow, including the position of the velocity maxima, for both the streamwise velocity profile and the cross-stream velocity profile. The latter is particularly important for the sediment-transport results presented later as the accurate prediction of secondary flows is important to accurate prediction of scour and fill in the bends of the meander reach.

A partial list of model output includes scalar quantities of water-surface elevation, velocity, depth, bed shear stress, and erosion rate and vector quantities of velocity and sediment flux. An example of model output that includes the velocity magnitude over the entire modeled reach and a detailed close-up that includes the erosion rate and vectors of sediment flux is shown in Fig. 8.

Hydraulic Characteristics of Spawning Location

One of the objectives of this study was to characterize local hydraulic conditions in the spawning reach that may serve as cues for sturgeon spawning site selection. A conceptual model of sturgeon spawning behavior based on hydraulic parameters in the current spawning reach might lead to a better understanding of why sturgeon does not appear to spawn further upstream in the braided reach or migrate through the braided reach to spawn further upstream in the canyon reach (in what appears to be better spawning and incubation habitat). Typically, models of spawning habitat are developed based on the suitability of velocity, depth, and substrate particle size (Crance 1986; Parsley et al. 1993; Parsley and Beckman 1994). For example, spawning suitability is generally described in terms of a range of desired velocity or depth from values measured near the time of spawning at egg-collection locations. White sturgeon spawning in any river basin

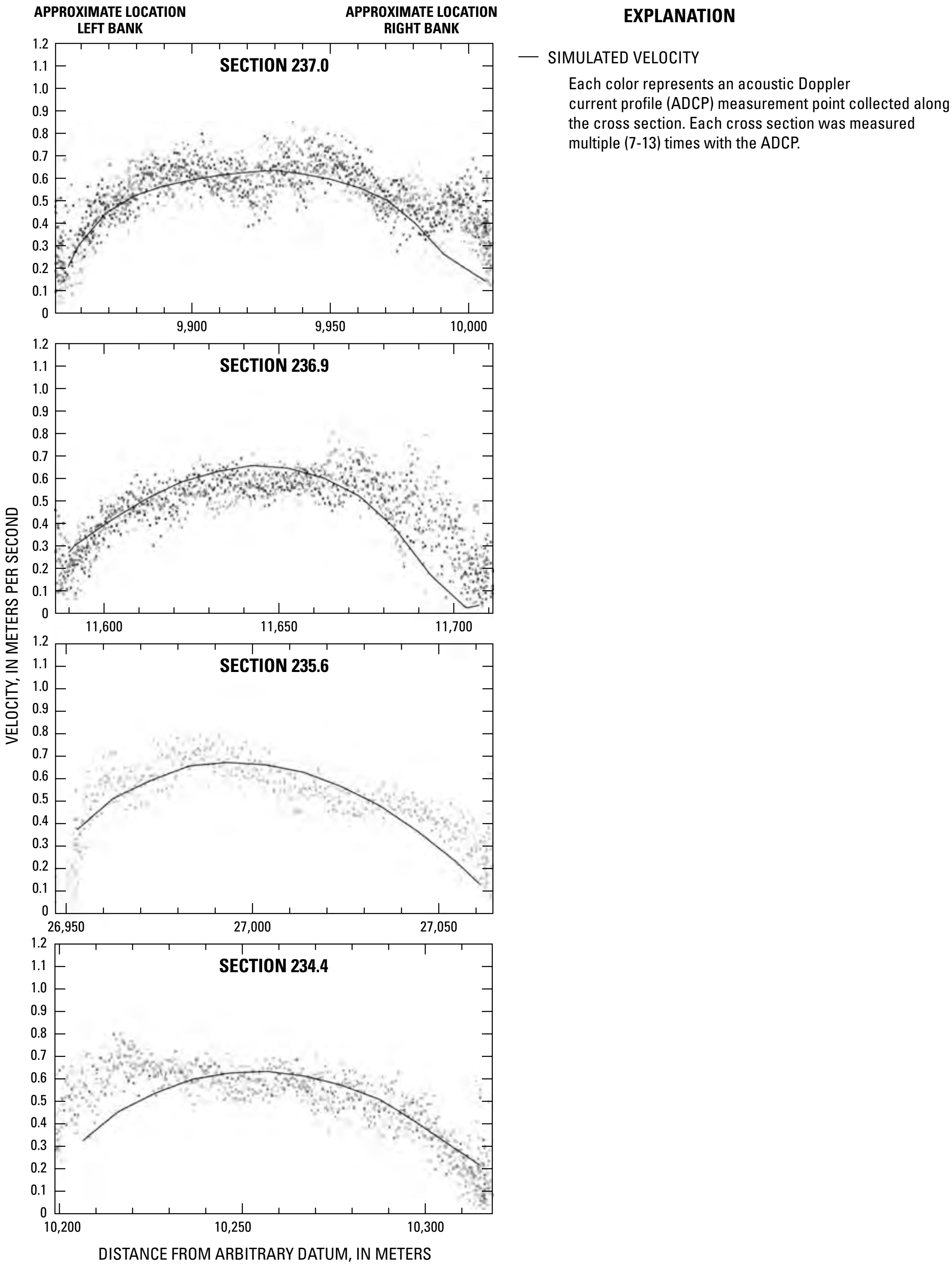

Fig. 6. Measured and simulated cross sections of vertically averaged velocity in the modeled reach for a steady flow that averaged 538 m^3/s on August 12–14, 2003. The simulated velocity is shown as the black line, and each of the 7–15 passes of the ADCP across each cross section is represented by a different shade.

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 hydrodynamic model such as the one used here is that 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 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. The microhabitat for Kootenai River white sturgeon spawning has been previously described as water depths within

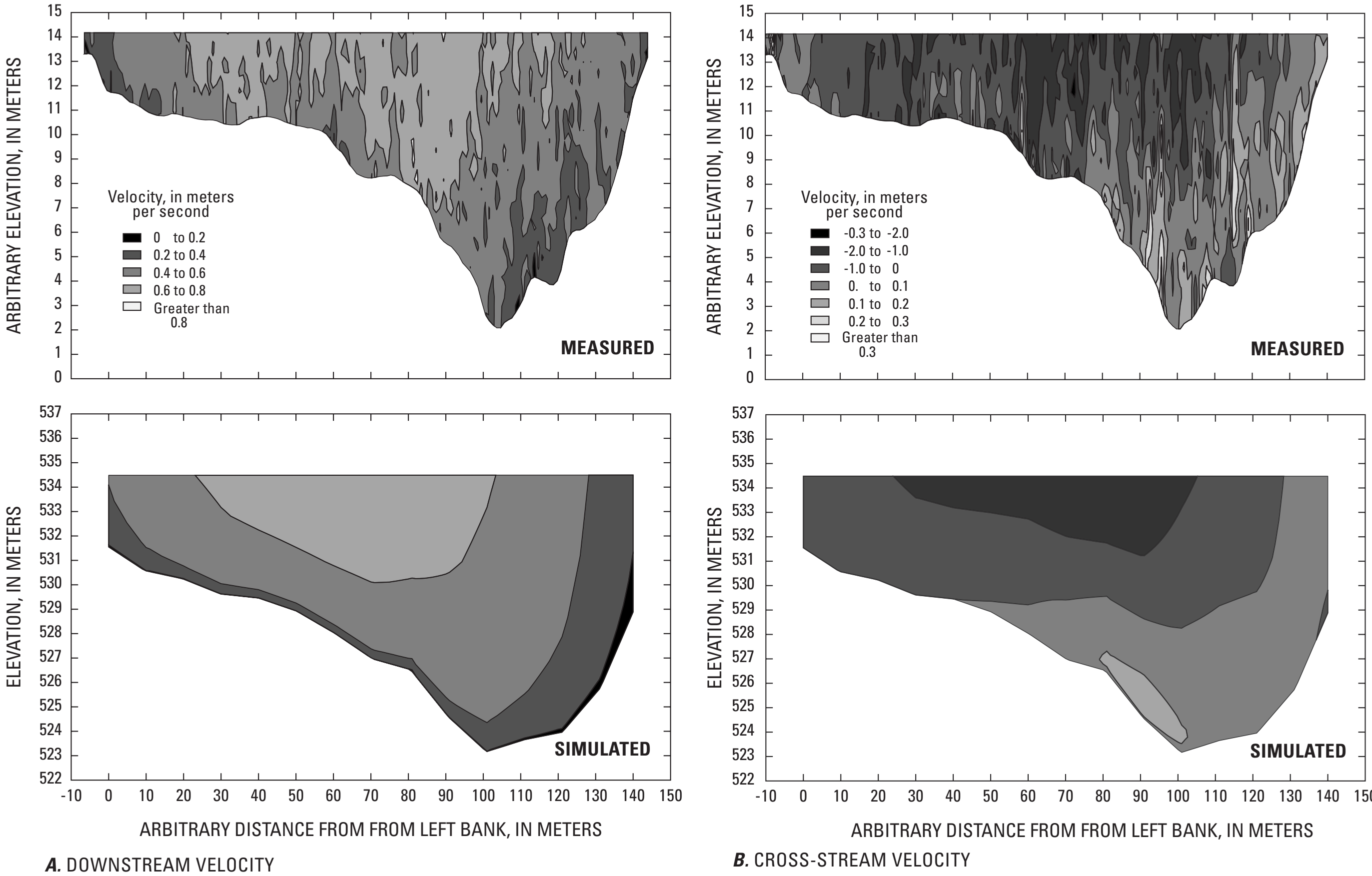

Fig. 7. Measured and simulated vertical profiles of (a) streamwise velocity; (b) cross-stream velocity at Section 237.0

the main channel usually exceeding 5 m, velocities of 0.5–1.0 m/s, sand substrate, and temperatures frequently between 8.5 and 12°C (Paragamian et al. 2001).

Velocity and Depth

White sturgeon spawning in the Kootenai River from 1994 to 2002 occurred over a range of discharges between approximately 500 and 1,500 m^3/s. To compare model simulations of velocity and depth, five time periods were selected from the historical record when the discharge was both relatively constant for 2 or more days and fell within the range of discharge found during typical spawning events. The values of velocity and depth were extracted from the model solution for each of the five modeled discharges at an interval of 0.1 km along the thalweg. The sampling for sturgeon eggs occurred prior to the wide use of GPS for positioning, and the sample locations were recorded as the position of the thalweg at a specific rkm; the precise location within the cross section or thalweg is not known. Therefore, at each location in the thalweg we determined the cross-sectional minimum, average, and maximum values of depth and vertically averaged velocity to provide more information about the range of conditions at each sampling location. The normalized maximum cross-sectional velocity in each cross section and SEPUE is shown in Fig. 6(a). The location of the spawning events coincides with a broad region of generally higher velocities. The normalized maximum cross-sectional depth in each cross section is shown in Fig. 7(a).

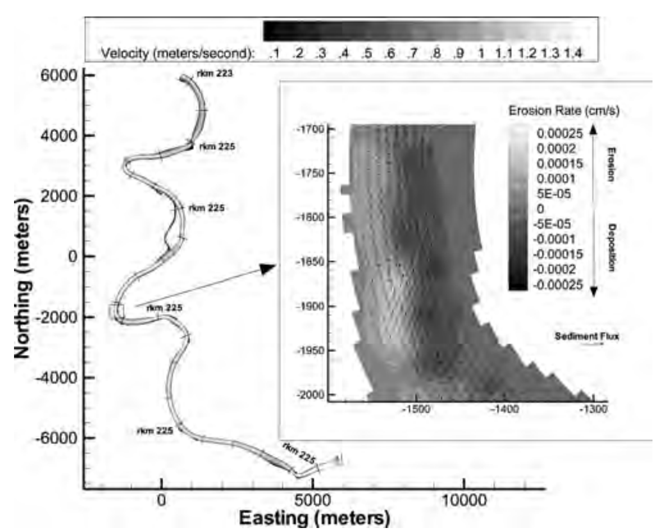

Fig. 8. Solution from a modeled discharge of 1,400 m^3/s is shown for the entire modeled reach. The direction of flow is from the bottom to the top. rkm markings are shown every 1 rkm and labeled every 5 rkm. The critical habitat reach is between rkm 228 and 246. The simulated vertically averaged velocity ranged from 0 to 1.7 m/s. Note the relatively low velocity found in the lower 3–4 rkm and the regions of higher velocity in the outside of the meander bends upstream. To illustrate the details of the model a short reach is shown that includes vectors of sediment flux and erosion rate.

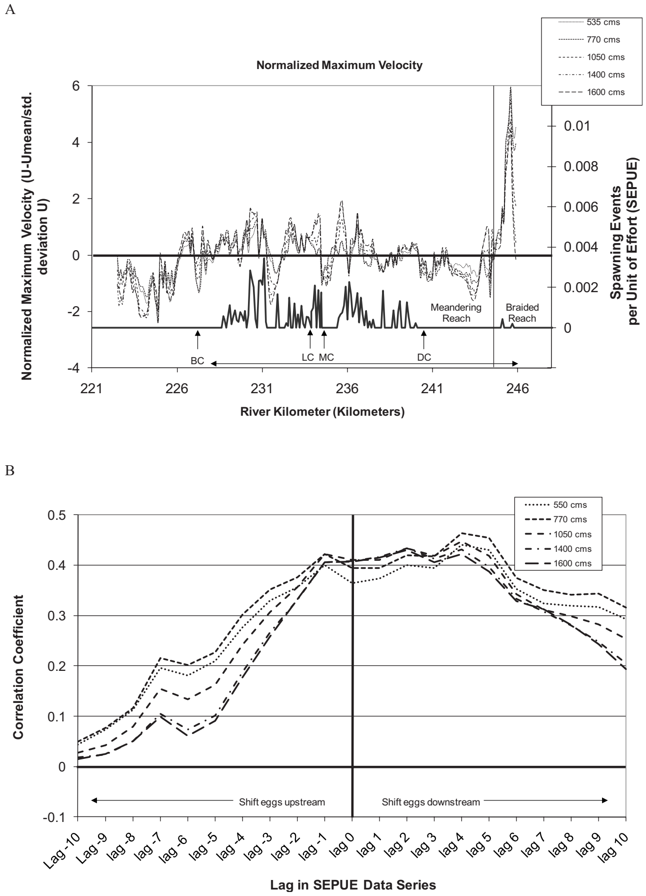

Fig. 9. (a) Normalized maximum vertically averaged velocity $(U - U_{\text{mean}})$/(standard deviation U), where U=maximum vertically averaged velocity; U_{mean}=mean of U at all extracted cross sections of the modeled reach; and the standard deviation U=standard deviation of U at all cross sections in the modeled reach, and SEPUE as a function of rkm. Following the thalweg of the flow solution, the maximum vertically averaged cross-sectional velocity is extracted from the model results at cross sections located every 0.1 km along. The results are shown for five modeled discharges ranging from 535 to 1,600 m^3/s. These discharges span the range of discharges that occurred during the spawning seasons from 1992 to 2002. The upward pointing arrows indicate the location of tributaries (Fig. 2) where DC=Deep Creek; MC=Myrtle Creek; LC=Lost Creek; and BC=Ball Creek. The horizontal black arrow indicates the span of the critical habitat reach. (b) The correlation between maximum vertically averaged velocity at each modeled discharge and the SEPUE. A positive lag of 1 corresponds to shifting SEPUE downstream by 0.1 rkm and a negative lag corresponds to shifting SEPUE upstream by 0.1 rkm.

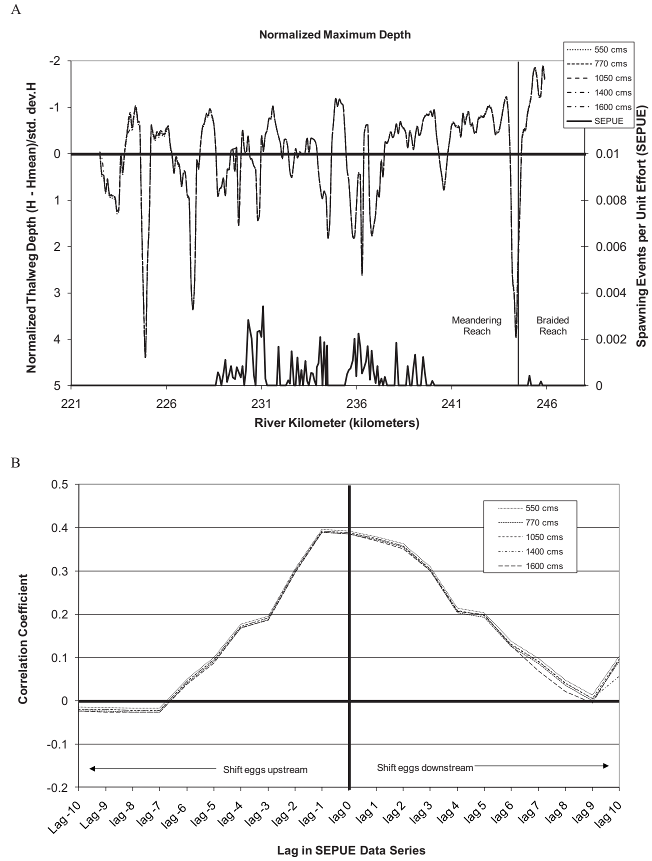

Fig. 10. (a) Normalized maximum depth $(H - H_{\text{mean}})$/(standard deviation H), where H=maximum cross-sectional depth; H_{mean}=mean of H in the modeled reach; and the standard deviation H=standard deviation of H in the modeled reach, and SEPUE as a function of rkm. Following the thalweg of the flow solution, the maximum vertically averaged cross-sectional velocity is extracted from the model results at cross sections located every 0.1 km along. The results are shown for five modeled discharges ranging from 535 to 1,600 m^3/s. These discharges span the range of discharges that occurred during the spawning seasons from 1992 to 2002. (b) The correlation between maximum depth and SEPUE (see Fig. 5 for the definition of the lag).

Correlation with Sturgeon Spawning Locations

Qualitatively [Figs. 9(a) and 10(a)] there appears to be a positive correlation between spawning location, as identified by the proxy of egg locations, and both high maximum velocity and high maximum depth. To test this observation, a spatial correlation was computed between spawning location and maximum velocity and maximum depth by shifting the spawning location over a 1.0-km range both downstream (positive lag) and upstream (negative lag) by 0.1-km increments [Figs. 9(b) and 10(b)]. The resulting correlations, reported as R values and with significance at the 99th percentile, while not particularly robust, revealed a broad region of positive correlation. The maximum correlation occurs between a lag of −1 and a lag of 6; in other words, shifting the egg locations upstream by 0.1 km or downstream by 0.6 km results in nearly the same correlation value. There is also a slight asymmetry in the correlations which is expressed in the correlation values decreasing faster with negative lags than with positive lags. Both patterns are consistent with the assumption that the eggs are released somewhere in the water column near the upstream end of high velocity zones and as they settle to the bottom of the river, or roll along the bottom of the river, they move in the streamwise direction. Correlations calculated between the average velocity and average depth but not reported here were not as conclusive. The correlation results support the results of previous studies that found sturgeon tends to select regions of higher velocity and greater depth (McCabe and Tracy 1994; Parsley et al. 1993; Parsley and Beckman 1994). However, these results do not provide evidence for a particular threshold velocity or even a specific range of velocity sturgeon select, rather, all other things considered (such as sufficient discharge and temperature), they appear to select higher velocity and greater depth within the spawning region for the given discharge when the fish are physiologically

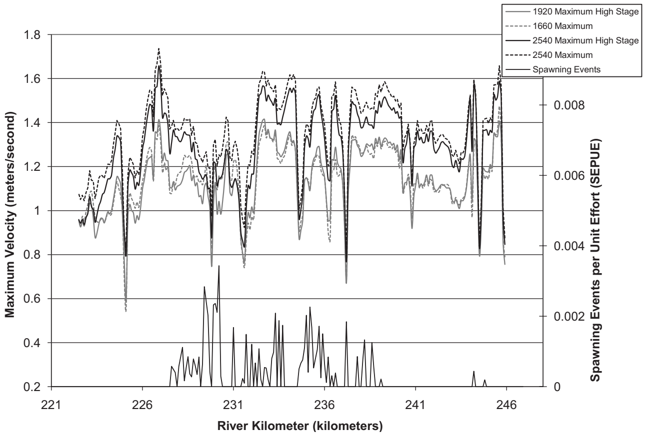

Fig. 11. To illustrate the effect of backwater on the pattern of maximum velocities in the Kootenai River, two pairs of discharges are simulated: (1) $1,920\ \mathrm{m}^3/\mathrm{s}$ with predam high lake stage and $1,660\ \mathrm{m}^3/\mathrm{s}$ with postdam lake stage and (2) $2,540\ \mathrm{m}^3/\mathrm{s}$ with high predam lake stage and 2,540 with low predam lake stage. Each discharge magnitude is close to the predam annual peak discharge of $2,200\ \mathrm{m}^3/\mathrm{s}$.

ready to spawn. This interpretation suggests that spawning fish will seek out the best perceived location to deposit eggs given the current environmental conditions.

Effect of Backwater on Spawning Site Selection

Normalized maximum cross-sectional velocity, in each cross section, was extracted from four model simulations with a range of discharges close to the predam mean annual peak flow ($2,200\ \mathrm{m}^3/\mathrm{s}$) with both predam high and low Kootenay Lake stages (Fig. 11). Kootenay Lake stage is varied to account for its effect on the upstream extent of backwater for a given discharge. Duke et al. (1999) hypothesized that higher predam Kootenay Lake stage reduced velocities in the meandering reach and encouraged sturgeon to move into the braided reach where the velocities would be higher. The limited number of simulations performed in this study indicated that the velocity may be slightly reduced in the meandering reach under higher lake stages compared to lower lake stages. However, the decrease in simulated velocity using the highest lake stages relative to that found using the lowest lake stages is relatively small, and the spatial variability in the simulated velocity pattern remains relatively unchanged. Thus, it seems unlikely that high lake levels could significantly alter the selection of spawning areas within the critical habitat reach.

Sediment-Transport Modeling

The only year with natural reproduction measured by catch of 20 or more Kootenai River white sturgeons during the postdam period was 1974. Uniquely this year had both high discharge ($\sim 1,300\ \mathrm{m}^3/\mathrm{s}$) and relatively long flow period (14 days) in early May, prior to the spawning season, compared to any other year in the postdam record (Fig. 3). Flow regulation has long been postulated as a factor limiting natural recruitment for various reasons, including diminished migration cues and reduced transport of fine-grained sand in the system, leaving potential coarse material buried where sturgeon currently spawn. As noted previously, there is 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. The hydrograph was idealized to a steady-flow period of 14 days at a constant discharge of $1,300\ \mathrm{m}^3/\mathrm{s}$, 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.

Several specific assumptions were used in the model: (1) the upstream sediment supply boundary condition of the modeling reach was set such that the upstream transport of sediment into the modeling reach was equal to the hydraulically determined capacity at the upstream boundary (i.e., the sediment-transport capacity was set equal to that calculated from the grain size and predicted bed shear stress at the upstream boundary); (2) a mean grain size (0.2 mm) equivalent to the existing bed material was used; (3) only a single grain size was considered; and (4) we used the Engelund-Hansen total load equation (Engelund and Hansen 1967) to determine the transport rate. Details of the sediment-transport model can be found in Nelson et al. (2003).

Fig. 12 shows the initial and ending topographies for a small portion of the meandering reach of river at 234–235 rkm. This reach lies within the current spawning reach. Note that there is generalized scour of approximately 1 m, as shown by the negative change in elevation in Fig. 12(d) throughout the outside of the meander bend and more locally intensive scour of up to approximately 3 m near the apex of the meander bend. Based on the core records from this location, as shown in Fig. 2, the scour would be sufficient to at least partially expose some buried gravel and cobble. This suggests that the flow in 1974 may have uncovered gravel in the current reach, thereby explaining the successful recruitment in that year.

However, these results should be viewed with some degree of caution. Although there is relatively high confidence in the pattern of scour and deposition, as shown in Figs. 12(c and d), 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, the scour could be greater or less depending on the distance from the upstream end of the reach and the quantitative disparity between the assumed and the actual supply. Furthermore, the elevation of the topography at any point in time depends on the actual morphology of the bed, and the computations were started with the current topography, not the topography that existed on the bed prior to the high-flow event in 1974. The results clearly indicate the potential for flow with magnitude and duration similar to that in 1974 to scour the bed and expose limited patches of suitable substrate. However, it should also be noted that many biotic and abiotic conditions experienced by sturgeon embryos in the Kootenai River today vary considerably from those of 1974, including increased water clarity, altered predator/prey ratios, and severely reduced population fecundity (Paragamian 2002; Paragamian et al. 2005). In other words, currently providing a 1974 hydrograph might not produce a year class similar to that of 1974 due to limiting factors in addition to those of the postdevelopment physical environment.

2006 High Discharge Event and Model Validation

During the 2006 runoff season Libby Dam released a 40-day sustained discharge above $1,000\ \mathrm{m}^3/\mathrm{s}$ between May 17th and June

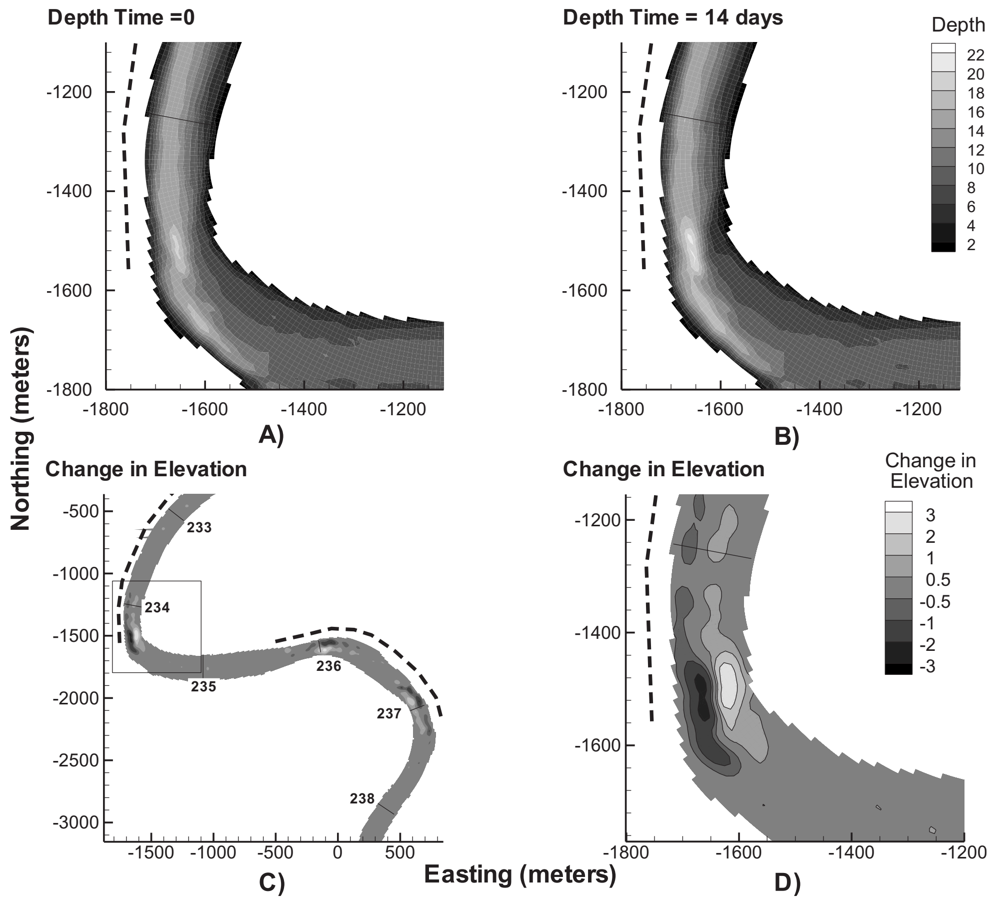

Fig. 12. Results of the morphodynamic simulation for a 14-day period with a constant discharge of $1{,}300\ \mathrm{m^3/s}$. (a) The depth at time=0; (b) time=14 days. The change in elevation over the 14-day period at the two large meander bends near Myrtle Creek, with the area shown in (a), (b), and (d) delineated in (c). The dashed lines adjacent to the channel show the approximate locations of spawning activity from 1994 to 2002 (see also Fig. 4). The solid black lines across the channel indicate the approximate rkm location. The greatest change in elevation occurs in the apex of the meander bends with scour in the thalweg and adjacent deposition on the point bars. A close-up of the scour and deposition near the Myrtle Creek bend is shown in (d).

25th. The flow reached a mean daily discharge of $1{,}730\ \mathrm{m^3/s}$ on June 18th and spent 12 days above $1{,}300\ \mathrm{m^3/s}$ during the period of June 11th–22th. While the discharge was the largest in the postdam period it did not quite approach the magnitude and duration of flows recorded in the predam period (Fig. 13). As stated in the original recovery plan for Kootenai River white sturgeon (Duke et al. 1999), significant changes in the natural flow regime since operation of Libby Dam are considered to be the primary reason for the decline of white sturgeon. However, since publication of the recovery plan uncertainty has arisen over the connection between natural flows and successful recruitment of white sturgeon. On one hand there is the idea that prior to managed flows out of Libby Dam the sturgeon must have used the reach of river above Bonners Ferry where there is suitable substrate. High discharge in combination with high predam Kootenay Lake stages is presumed to have increased the upstream extent of backwater such that the transition between the relatively fast, shallow, and free-flowing water and the relatively slow, deep, and backwater conditions occurred above Bonners Ferry in the braided reach, where there is suitable coarse substrate. On the other hand is the idea that the sturgeons are spawning where they have always spawned and the current lack of high flows during the spawning season limits the transport potential, leaving the bed composed of fine-grained sand rather than scouring the bed and exposing gravel lag deposits. The high discharge event in 2006 occurred after the original analysis of both the spawning site selection and the potential for high 1974-like discharge event to sufficiently scour the bed in the existing spawning reach provides an opportunity to validate our understanding of the effect of a near predam high flow on sturgeon spawning behavior and the effect of high flows on substrate composition.

During the high-flow event in 2006, of the 29 tagged adult white sturgeons that were in spawning condition, 27 moved as far upstream as rkm 235.2 (above Myrtle Creek), 23 moved as far upstream as rkm 239 (just below Deep Creek), 12 went as far upstream as rkm 243.5 (Ambush Rock), 9 went as far as rkm 245 (bottom of the braided reach), 5 went as far as rkm 246.8, and 2 went as far as rkm 248.6. These last two fish moved well into the braided reach where the channel becomes much shallower and multithreaded. Results of a 1D model of flow in this reach (Berenbrock 2005) show almost a doubling of average velocity at rkm 249 compared to most of the reach downstream from rkm 249. The other region of relatively high velocity is that found in the transition reach, near Bonners Ferry. Here there are consistently higher velocities than in the meandering reach downstream. Prior to the 2006 high-flow event, no sturgeon had been tracked above this region of higher-flow velocities (Paragamian et al. 2002; Rust and Wakkinen 2005, 2007; Rust et al. 2007). Thus it appears that

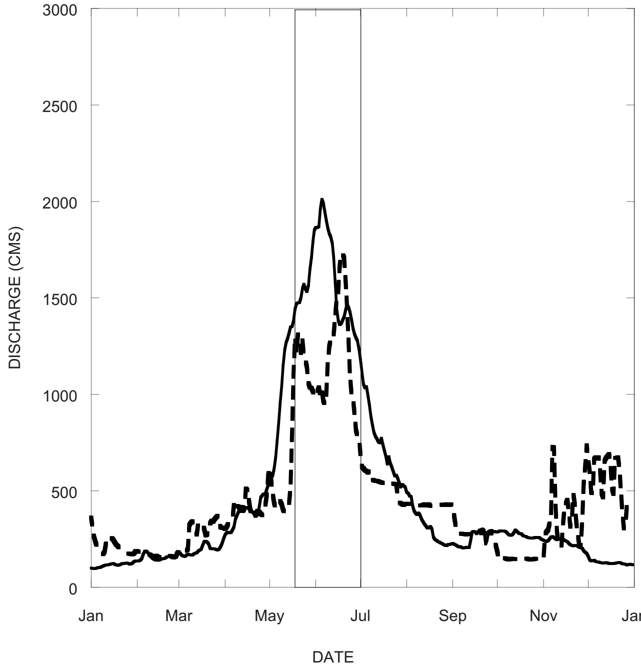

Fig. 13. Hydrographs of the predam average annual mean daily discharge for the years 1966–1971 (solid line) and the mean daily discharge during 2006 (dashed line)

while the sturgeons are keying on regions of high velocity for spawning in the meandering reach, there may be a threshold maximum velocity they cannot swim through to access the braided reach.

The results of our analysis suggest that sturgeons are spawning in areas of highest available velocity and depths over a range of flows. The effect of the relatively high backwater conditions on velocity and depth is small, resulting in slight decreases in velocity magnitude and slight increases in depth, but the spatial pattern of spawning-related hydraulic conditions remains intact. Regardless of the discharge and backwater conditions, the resulting pattern of velocity and depth provides potential spawning locations throughout the meander reach, all of which appear to be used. Indeed, during the high flow of 2006, sturgeon eggs were collected in the spawning reach between rkm 229.5–230.3, rkm 236.3, and rkm 245.5 (Rust and Wakkinen 2007). In other words, the high discharge in 2006 was associated with only a small number of fish moving into the braided reach while the majority of fish remained within the meandering reach and at least a few of these fish spawned there. High flows representing historical predam conditions do not appear to promote the expansion of spawning into the braided reach. This suggests that recruitment failure is not caused by an alteration in spawning location.

The high-flow event during 2006 provides an ideal opportunity to test the hypothesis that high-magnitude long-duration flow events are sufficient to scour the bed and expose coarse gravel lag deposits. The flow and sediment-transport model was applied keeping all things equal to the simulations presented in Fig. 12 and discussed above with the exception of the hydrograph, which was taken as the 15-min discharge data from the USGS Tribal Hatchery gauge (12310100), located on the Kootenai River 0.8 rkm upstream from the mouth of Deep Creek from the 48-day period May 15th to July 2nd (http://waterdata.usgs.gov/nwis). The magnitude of scour in the thalweg and deposition on the point bar is similar to that in the previous simulation that held the

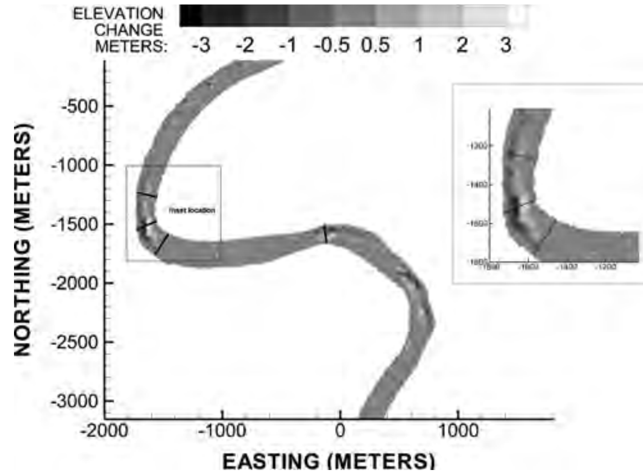

Fig. 14. Results of the morphodynamic simulation showing the change in elevation over the 48-day period between May 15 and July 2, 2006. (a) An overview of two large meander bends near Myrtle Creek. The location of video cross sections in this reach following the high flow in early July is identified as black lines. The inset (b) is a close-up of the region near Myrtle Creek [see Fig. 12(d) for a comparison].

discharge constant over a 14-day period, with the exception of a slightly longer streamwise extent of the scour and deposition (Fig. 14).

Following the peak discharge in late June the substrate was surveyed with video equipment at seven cross sections in the river (Fig. 2). The initial video cross sections focused on the reach between rkm 233.5 and 234.5 because of the proximity to Myrtle and Lost Creeks, the large number of spawning events in this small reach, and the favorable results of the sediment-transport simulations, suggesting that the scour potential was sufficient to reveal a buried coarse lag deposit. In addition to the video cross section collected in this reach sampling was carried out downstream from Ball Creek and in the meander bend upstream from Myrtle Creek. The Ball Creek surveys provided an additional site downstream from tributaries, and the survey above Myrtle Creek provided a site whose nearest tributary is approximately 4 rkm upstream.

Images of substrate were collected primarily in meander bends with the exception of the cross section at the Myrtle Creek confluence which was located upstream from a river bend. In meander bends the images reveal that the bed is composed of steps eroded into lacustrine clays in the outside of the meander bend, the thalweg is composed of gravel and cobble substrate, and the inside of the bend, or the point bar deposit, is composed of sand size material (Fig. 15). On the surface of the lacustrine steps gravel and cobbles were found in pockets of varying sizes. These steps often have crevasselike troughs oriented in the direction of flow. The step risers are fractured with angular blocks of the lacustrine clay lying at the base of the step. The clay steps have features similar to a bedrock surface but are instead composed of well-indurated clay. Strikingly, the clay step surfaces and pockets are nearly devoid of sand. The thalweg has large patches of clean gravel and cobbles up to 10 cm in size. The cobbles are well rounded and composed of many varying lithologies, as evidenced by the change in color and texture. In a number of the cross sections there was a clear transition from coarse material in the thalweg to the fine sand deposits of the meander point bars, where the gravels are overlain by sand.

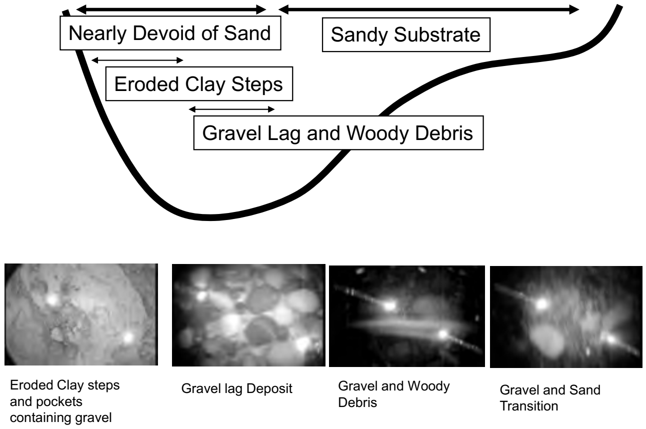

Fig. 15. Idealized cross section of the channel substrate, in a meander bend, following a high-flow scouring event. The outside of the bend through the thalweg is nearly devoid of sand and composed of lacustrine clay steps, and gravel/cobble lag deposits occur in the thalweg. Patches of new and old woody debris are often found in the thalweg. The inside of the bed is composed of fine sandy material forming the point bar deposit.

The cross section at the Myrtle Creek confluence showed more angular substrate on the right bank downstream from the confluence with Myrtle Creek where there was also substantial woody debris; however, most of the cross section consisted of a sandy surface that was interspersed by a few clean lacustrine clay surfaces and one small patch of coarse material with grain sizes larger than 10 cm. The presence of more sand and less lacustrine surfaces suggests that there is less scour in this cross section than the others, which is consistent with the modeling results.

The pattern of substrate composition at each of the video cross sections surveyed within meander bends (Fig. 15) qualitatively corroborates the patterns of scour in the model simulations of the high-flow events in 1974 and 2006 and the existence of gravel and cobble lag deposits where the vibracore studies previously found gravel and cobble substrate covered by sand. The consistent presence of gravel and cobble located in the thalweg suggests that following a period of significant high flow such as that experienced in 2006, gravel and cobble lag deposits are likely to be unveiled throughout much of the thalweg in the meander bends of the Kootenai River. Perhaps more revealing is the complexity of the channel bottom in the meander bends. Where surveyed there were extensive portions of the bed composed of lacustrine steps that were nearly sand free. These lacustrine steps, unveiled of sand, may provide a viable spawning substrate, not yet considered, in addition to gravel and cobble substrates. Hard clay has been identified as spawning substrate for other sturgeon species such as the Gulf sturgeon [U.S. Fish and Wildlife Service (USFWS) 2003] and Atlantic sturgeon (Wilson and McKinley 2004).

Paragamian et al. (2001) noted that the Kootenai River white sturgeon uses 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 1 year to another created variability in the distribution of exposed, coarse substrate depending on the downstream transport of coarse material from the locations upstream and local inputs of coarse material from tributaries; therefore, the location of suitable substrate varied from 1 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.

Conclusions

The goal of this investigation was to integrate a detailed data set of white sturgeon spawning locations during 1994–2002, as represented by egg-collection locations and the spatially distributed results from a multidimensional model of flow and sediment transport to gain insight to the following questions about white sturgeon spawning in the Kootenai River. Are white sturgeon responding to false environmental cues created by flow regulation and spawning outside the historic spawning reach? Or are white sturgeon spawning in the historic spawning reach, but in the present managed flow regime, this reach lacks the energy necessary to scour the bed and expose coarse-grained substrate suitable for egg incubation?

The analysis of the model simulations demonstrates that the white sturgeon spawning locations in the meander reach coincide with a broad region of high velocity which is higher than that found downstream; thus the sturgeon appears to migrate to a reach with higher velocities. Within this broad region of high velocity the white sturgeon spawn in the meander bends where the velocities and depths are locally higher, as indicated by the model results and the spatial correlation analysis. The locations of high velocity and depth in the meander bends are consistent at both pre- and postdam discharge magnitudes. Thus, the hydraulic cues currently used for spawning existed prior to flow management and suggest that the current and historical spawning reaches are the same. This assertion is supported by the migration patterns of 29 radio-tagged white sturgeon during the 2006 high-flow event which had discharge magnitude and duration near that found in the predam period. A large number (24) of these sturgeons migrated into the current spawning reach where spawning was recorded by egg mats at three locations. Only five sturgeons were recorded in the lower 2.5 km of the braided reach. High predam flows do not appear to promote the expansion of spawning into the braided reach. This suggests that recruitment failure is not caused by an alteration in spawning location.

Prior coring studies identified the existence of buried gravel and cobble lenses under one to several meters of sand in the current spawning reach. A flow and sediment-transport model simulation of the high discharge prior to the spawning season during 1974, the only year in the postdam period with significant recruitment of juvenal white sturgeon, indicated the potential of high discharge to scour the sand and expose these regions of buried gravel and cobble. Model simulations of scour during the 2006 high-flow event predicted sufficient scour to uncover the buried gravel and cobble. A video survey of the channel substrate following the high-flow event in 2006 revealed the existence of gravel and cobble in the thalweg of the channel where core records indicated the presence of these coarser substrates buried by sand. Most Libby Dam era discharges have been incapable of scouring and exposing areas that have suitable incubation substrates. The sandy substrate likely remains a major bottleneck. Kootenai River white sturgeons are likely spawning in pre-Libby Dam locations but postdam river regulations have rendered the meander reach habitat unsuitable for incubation and rearing of white sturgeon progeny resulting in recruitment failures.

Acknowledgements

The writers would like to thank Sue Ireland and the Kootenai Tribe of Idaho for their kind support. Rick Backsend, John Gralow, and Russ Christensen, Post Falls, Idaho, and Edward Moran, Anchorage, Alaska, all with the U.S. Geological Survey, worked long hours collecting data on the Kootenai River for this project. This work was funded by the U.S. Geological Survey National Research Program.

References

Anders, P. J., Richards, D. L., and Powell, M. S. (2002). "The first endangered white sturgeon population (*Acipenser transmontanus*): Repercussions in an altered large river-floodplain ecosystem." *Biology, Management and Protection of North American Sturgeons. American Fisheries Society Symp. 28*, W. Van Winkle, P. Anders, D. Dixon, and D. Secor, eds., American Fisheries Society, Bethesda, MD, 67–82.

Barton, G. J. (2004). "Characterization of channel substrate, and changes in suspended-sediment transport and channel geometry in white sturgeon spawning habitat in the Kootenai River near Bonners Ferry, Idaho, following the closure of Libby Dam." *USGS Water-Resources Investigations Rep. No. 03-4324*.

Barton, G. J., McDonald, R. R., and Nelson, J. M. (2009). "Simulation of streamflow using a multidimensional flow model for white sturgeon habitat, Kootenai River near Bonners Ferry, Idaho—A supplement to Scientific Investigations Report 2005–5230." *USGS Scientific Investigations Rep. No. 2009-5026*.

Barton, G. J., McDonald, R. R., Nelson, J. M., and Dinehart, R. L. (2005). "Simulation of flow and sediment mobility using a multidimensional flow model for the white sturgeon critical-habitat reach, Kootenai River near Bonners Ferry, Idaho." *USGS Scientific Investigations Rep. No. 2005-5230*.

Barton, G. J., and Moran, E. H. (2004). "Surveying cross sections of the Kootenai River between Libby Dam, Montana, and Kootenay Lake, British Columbia, Canada." *USGS Open-File Rep. No. 2004-1045*.

Berenbrock, C. (2005). "Simulation of hydraulic characteristics in the white sturgeon spawning habitat of the Kootenai River near Bonners Ferry, Idaho." *USGS Scientific Investigations Rep. No. 2005-5110*.

Berenbrock, C. (2006). "Simulations of hydraulic characteristics for an upstream extension of the white sturgeon habitat of the Kootenai River near Bonners Ferry, Idaho—A supplement to Scientific Investigations Report 2005–5110." *USGS Scientific Investigations Rep. No. 2006-5019*.

Berenbrock, C., and Bennett, J. P. (2005). "Simulation of flow and sediment transport in the white sturgeon spawning habitat of the Kootenai River near Bonners Ferry, Idaho." *USGS Scientific Investigations Rep. No. 2005-5173*.

Conte, F. C., Doroshov, S. I., Lutes, P. B., and Strange, E. M. (1988). "Hatchery manual for the white sturgeon *Acipenser transmontanus* Richardson, with application to other North American Acipenseridae." *Cooperative Extension, Div. of Agriculture and Natural Resources, Univ. of California Publication 3322*.

Coutant, C. C. (2004). "A riparian habitat hypothesis for successful reproduction of white sturgeon." *Reviews in Fisheries Science*, 12(1), 23–73.

Crance, J. H. (1986). "Habitat suitability index models and instream flow suitability curves: Shortnose sturgeon." *U.S. Fish and Wildlife Service Biological Rep. No. 82(10.129)*.

Daley, R. J., Carmack, E. C., Gray, C. B., Pharo, C. H., Jasper, S., and Weigand, R. C. (1981). *The effects of upstream impoundments on Kootenay Lake, B.C.*, Scientific Series 117, National Water Research Institute, Vancouver, B.C.

Dinehart, R. L., and Burau, J. R. (2005). "Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river." *J. Hydrol.*, 314, 1–21.

Duke, S., et al. (1999). "Recovery plan for Kootenai River white sturgeon." *J. Appl. Ichthyol.*, 15, 157–163.

Engelund, F., and Hansen, E. (1967). *A monograph on sediment transport*, Teknisk, Forlag, Copenhagen, Denmark.

Golder Associates. (2005). "Analysis of white sturgeon spawning in relation to the Waneta Dam white sturgeon flow augmentation program." *Final Rep. to Teck Cominco Metals Ltd.*.

Kock, T. J., Congleton, J. L., and Anders, P. J. (2006). "Effects of sediment cover on survival and development of white sturgeon embryos." *N. Am. J. Fish. Manage.*, 26, 134–141.

Kohlhorst, D. W. (1976). "Sturgeon spawning in the Sacramento River in 1973, as determined by distribution of larvae." *California Fish and Game*, 62(1), 32–40.

McCabe, G. T., and Beckman, L. G. (1990). "Use of an artificial substrate to collect white sturgeon eggs." *California Fish and Game*, 76(4), 248–250.

McCabe, G. T., and Tracy, C. A. (1994). "Spawning and early life history of white sturgeon, *Acipenser transmontanus*, in the lower Columbia River." *Fish. Bull.*, 92, 760–772.

McDonald, R. R., Nelson, J. M., and Bennett, J. P. (2005). "Multidimensional surface-water modeling system user's guide." *USGS Techniques in Water Resources Investigations 11-B2*.

Nelson, J. M., Bennett, J. P., and Wiele, S. M. (2003). *Flow and sediment-transport modeling. Tools in fluvial geomorphology*, Wiley, England, 539–576.

Nelson, J. M., and McDonald, R. R. (1996). "Mechanics and modeling of flow and bed evolution in lateral separation eddies." *Rep. to Grand Canyon Monitoring and Research Center*.

Nelson, J. M., and Smith, J. D. (1989). "Evolution and stability of erodible channel beds." *River meandering, AGU water resources monograph 12*, S. Ikeda and G. Parker, eds., American Geophysical Union, Washington, D.C., 321–377.

Pantankar, S. V. (1980). "Numerical heat transfer and fluid flow." Hemisphere Publishing Co., New York.

Paragamian, V. L. (2002). "Changes in the species composition of the fish community in a reach of the Kootenai river Idaho, after construction of Libby Dam." *Journal of Freshwater Ecology*, 3(17), 375–383.

Paragamian, V. L., Beamesderfer, R. P., and Ireland, S. C. (2005). "Status, population dynamics, and future prospects of the endangered Kootenai River white sturgeon population with and without hatchery intervention." *Trans. Am. Fish. Soc.*, 134, 518–532.

Paragamian, V. L., and Hansen, M. J. (2008). "Evaluation of recovery goals for endangered white sturgeon in the Kootenai River, Idaho, USA." *N. Am. J. Fish. Manage.*, 28, 562–470.

Paragamian, V. L., and Kruse, G. (2001). "Kootenai River white sturgeon spawning migration behavior and a predictive model." *N. Am. J. Fish. Manage.*, 21, 22–33.

Paragamian, V. L., Kruse, G., and Wakkinen, V. D. (1997). "Kootenai River white sturgeon investigations." *Prepared for Bonneville Power Admin. Ann. Prog. Rep.*, Proj. 88-65, Idaho Dept. of Fish and Game, Boise, Idaho.

Paragamian, V. L., Kruse, G., and Wakkinnen, V. D. (2001). "Spawning habitat of Kootenai River white sturgeon, post Libby Dam." *N. Am. J. Fish. Manage.*, 21, 10–21.

Paragamian, V. L., Wakkinnen, V. D., and Kruse, G. (2002). "Spawning locations and movement of Kootenai River white sturgeon." *J. Appl. Ichthyol.*, 18, 608–616.

Parsley, M. J., Anders, P. J., Miller, A. I., Beckman, L. G., and McCabe, G. T., Jr. (2002). "Recovery of white sturgeon populations through natural production: Understanding the influence of abiotic and biotic

factors on spawning and subsequent recruitment." *Biology, Management, and Protection on North American Sturgeon. American Fisheries Society*, *Symposium 28*, W. Van Winkle, P. J. Anders, D. H. Secor, and D. A. Dixon, eds., 55–66.
Parsley, M. J., and Beckman, L. G. (1994). "White sturgeon spawning and rearing habitat in the lower Columbia River." *N. Am. J. Fish. Manage.*, 14, 812–827.
Parsley, M. J., Beckman, L. G., and McCabe, G. T., Jr. (1993). "Spawning and rearing habitat used by white sturgeon in the Columbia River downstream of McNary Dam." *Trans. Am Fish. Soc.*, 122, 217–227.
Perrin, C. J., Heaton, A., and Laynes, M. A. (2000). "White sturgeon (*Acipenser transmontanus*) spawning habitat in the lower Fraser River." *Rep. prepared by Limnotek Research and Development Inc. for BC Fisheries*.
Perrin, C. J., Rempel, L. L., and Rosenau, M. L. (2003). "White sturgeon spawning habitat in an unregulated river: Fraser River, Canada." *Trans. Am. Fish. Soc.*, 132, 154–165.
Poff, N. L., et al. (1997). "The natural flow regime." *BioScience*, 47, 769–784.
Rattray, M., Jr., and Mitsuda, E. (1974). "Theoretical analysis of conditions in a sale wedge." *Estuarine Coastal Mar. Sci.*, 2, 373–394.
Richter, B. D., Boumgartner, J. V., Powell, J., and Braun, D. P. (1996). "A method for assessing hydrological alteration within ecosystems." *Conserv. Biol.*, 10(4), 1163–1174.
Rust, P. J., and Wakkinen, V. (2005). "Kootenai River white sturgeon spawning and recruitment evaluation." Prepared for Bonneville Power Administration, *IDFG Rep. No. 05-37*, Idaho Dept. of Fish and Game, Boise, Idaho.
Rust, P. J., and Wakkinen, V. (2007). "Kootenai River white sturgeon spawning and recruitment evaluation." Prepared for Bonneville Power Administration, *IDFG Rep. No. 07-54*, Idaho Dept. of Fish and Game, Boise, Idaho.
Rust, P. J., Wakkinen, V., and Kiser, T. (2007). "Kootenai River white sturgeon spawning and recruitment evaluation." Prepared for Bonneville Power Administration, *IDFG Rep. No. 07-23*, Idaho Dept. of Fish and Game, Boise, Idaho.
Schaffter, R. G. (1997). "White sturgeon spawning migrations and location of spawning habitat in the Sacramento River, California." *California Fish and Game*, 83(1), 1–20.
Scott, W. B., and Crossman, E. J. (1973). "Freshwater fishes of Canada." Fisheries Research Board of Canada, *Bulletin 184*.
Setter, A., and Brannon, E. (1990). "Report on Kootenai River white sturgeon electrophoretic studies—1989, Report for the Idaho Department of Fish and Game. Aquaculture Extension, Univ. of Idaho. Pp 30–50." *Kootenai River White Sturgeon Investigations and Experimental Culture. Annual Progress Rep. No. FY 1989*, K. A. Apperson, ed., Idaho Dept. of Fish and Game and Bonneville Power Administration, Portland, Ore., Contract No. DE-A179-88BP3497, Project No. 88-65.
Snyder, E. B., and Minshall, G. W. (1996). *Ecosystem metabolism and nutrient dynamics in the Kootenai River in relation to impoundment and flow enhancement of fisheries management*, Stream Ecology Center, Idaho State Univ., Boise, Idaho, variously paged.
U.S. Fish and Wildlife Service (USFWS). (1994). "Endangered and threatened wildlife and plants; determination of endangered status for the Kootenai River population of white sturgeon—Final rule." *Federal Register*, 59(171), 45989–46002.
U.S. Fish and Wildlife Service (USFWS). (2000). "Final biological opinion—Effects to listed species from operations of the Federal Columbia River Power System." *Consultation performed for US Army Corps of Engineers, Bonneville Power Administration, and US Bureau of Reclamation*, USFWS, Region 1, Portland, Ore., ⟨http://www.fws.gov/pacific/finalbiop/BiOp.pdf⟩ (2008).
U.S. Fish and Wildlife Service (USFWS). (2001). "Endangered and threatened wildlife and plants; final designation of critical habitat for the Kootenai River population of white sturgeon." *Federal Register*, 66(173), 46548–46561.
U.S. Fish and Wildlife Service (USFWS). (2003). "Critical habitat for Gulf sturgeon." *Federal Register*, 68(53), 13454.
USDA. (2007). "National resources conservation service." *ID601—Soil survey of Boundary County Area, Idaho*, *web soil survey*, available online at ⟨http://websoilsurvey.nrcs.usda.gov/⟩ (Jul. 18, 2007).
Weisel, C. (1980). "Soil survey of Boundary County area, Idaho." *U.S. Dept. of Agriculture, Natural Resources Conservation Service*, online at ⟨http://soils.usda.gov/survey/online_surveys/idaho/⟩ (2008).
Wilson, J. A., and McKinley, S. R. (2004). "Chapter 2: Distribution, habitat and movements." *Sturgeons and paddlefish of North America*, G. T. O. Lebreton, F. W. H. Beamish, and R. S. McKinley, eds., Kluwer Academic, The Netherlands, 40–72.