Temporal distribution of Kootenai River white sturgeon spawning events and the effect of flow and temperature

By V. L. Paragamian and V. D. Wakkinen

Idaho Department of Fish and Game, Coeur d'Alene, ID, USA

Summary

We examined the temporal distribution of endangered Kootenai River white sturgeon *Acipenser transmontanus* spawning, its relation to flow and temperature, and both natural and man-made variations thereof. We believed this information would be helpful because a Technical Management Team as well as the Kootenai River White Sturgeon Recovery Team manage flows, and, to a lesser degree, temperature thereof during each spawning season. Spawnings from 1994 to 2000 were monitored by egg collection using artificial substrate mats and subsequent microscopic examination of the eggs to estimate age and timing of spawning. The strength of our study was in correlation to observed spawning events with corresponding temperature and flow. We estimated that the number of white sturgeon spawning events ranged from nine to 20, with spawning days ranging from 17 to 31 days. Average daily temperature during spawning ranged from 7.5 to 14 °C, with the highest probability of spawning (48 %) at 9.5-9.9 °C. Average daily flow for spawning events ranged from 141 to 1265 m^3 s-1, but most (63%) spawning took place above 630 m^3 s^{-1}. Initial spawning by Kootenai River white sturgeon during spring may be synchronized with the arrival of females from downstream staging reaches. After the onset of spawning, the temporal distribution of spawning events appears to be dependent on the shape and stability of flow and temperature. We found a water temperature decrease of ≥0.8 °C could disrupt white sturgeon spawning. Our analysis suggests for optimum spawning in the Kootenai River that flows should be held above 630 m^3 s^{-1}, ideally 1200 m^3 s^{-1}, with a temperature range of 9.5-12 °C. Given the available flows, we found no evidence to suggest a need above 1300 m^3 s^{-1} for white sturgeon spawning, but there may be secondary benefits associated with higher flows.

Introduction

Flooding in the Kootenai River Basin of ID, USA, and British Columbia (BC), Canada, was once common. In 1966, the US Army Corps of Engineers (USACE) began construction of the Libby Dam on the Kootenai River, near Jennings, MT, USA, for flood control and hydropower (Fig. 1). The dam was completed in 1972, and Lake Koocanusa was impounded in 1973 and completely filled in 1974. After the dam construction, physical and chemical attributes of the river changed from the pre-dam conditions (Woods, 1982; Partridge, 1983; Snyder and Minshall, 1995). Historic pre-dam flows during the native white sturgeon *(Acipenser transmontanus)* spawning period ranged from 1416 to 2832 m^3 s^{-1}, but post-Libby Dam construction peak runoff events were generally in the range of 250-450 m3 s-1 (Fig. 2) (Duke et al., 1999). The river

temperature also changed, becoming about 1 °C cooler in the summer and 4 °C warmer in winter (Partridge, 1983) and the river was less productive (Woods, 1982; Snyder and Minshall, 1995). Within a decade of the dam operation, the white sturgeon population became recruitment-limited (Partridge, 1983; Apperson, 1990).

The Kootenai River white sturgeon was given endangered species status in ID and MT, USA,. on September 6, 1994. Under provisions of the Endangered Species Act, an international mufti-agency Kootenai River White Sturgeon Recovery Team (KRWSRT) was formed to develop and help coordinate implementation of a recovery plan (Duke et al., 1999). Two of the main recovery measures are to (i) re-establish a more natural flow pattern to help restore natural spawning, rearing and recruitment; and (ii) conduct conservation aquaculture (Ireland et al., 2002) to prevent extinction, and to maintain genetic integrity (Kincaid, 1993). The main task of the Idaho Department of Fish and Game was to evaluate white sturgeon movement, spawning and recruitment as well as to determine the effectiveness of experimental spring flow mitigation. The total number of spawning events each season is thought by the KRWSRT to be the best measure of the timing of flow mitigation and spawning performance.

Flow mitigation from Libby Dam for white sturgeon spawning and rearing is based on a tiered approach, depending primarily on the snow pack in the Kootenai drainage of the Canadian Rockies. The higher the snow pack, the greater the volume of water available for flow mitigation (Duke et al., 1999). A technical management team (TMT) determines the timing, volume, and shape of the flow release prior to each spawning season, based on input from the US Fish and Wildlife Service (USFWS). Our investigation objective was to determine the temporal distribution of white sturgeon spawning as related to natural and man-made variations in flow and temperature. Temperature is the primary environmental variable that determines the beginning of white sturgeon spawning (Parsley et al., 1993), and can be controlled to some degree by a selective withdrawal system at Libby Dam. However, in years of high runoff when more water is available for mitigated flows for white sturgeon, Lake Koocanusa stratifies only weakly, at best by the end of June, limiting temperature control and the availability of warmer water that might stimulate spawning. Flow is the most important variable that can be managed by the KRWSRT and TMT for recovery actions. Thus, this analysis would be helpful for them to determine the necessary timing and volume of spring flow mitigation to aid white sturgeon. There are other variables affecting white sturgeon spawning (Conte et al., 1988), but those of flow and temperature are the most manageable.
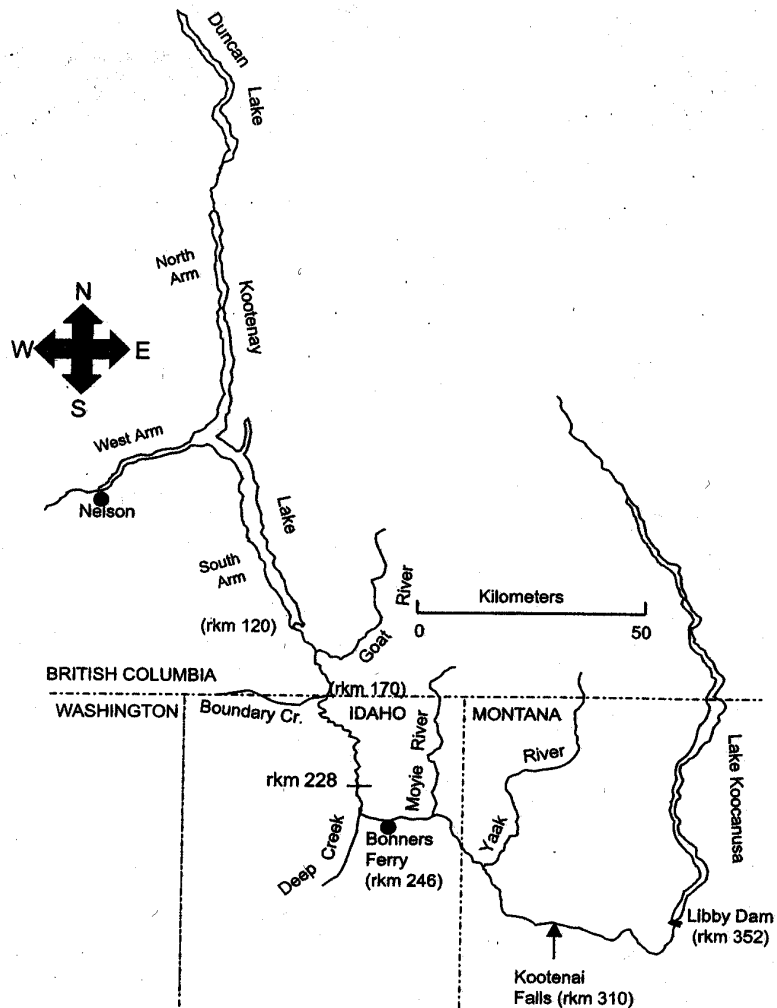
Fig 1. Location of the Kootenai River, Kootenay Lake, Lake Koocanusa, Libby Dam, Bonners Ferry, and important points. River distances from the northernmost reach of Kootenay Lake are in river kilometers (rkm) and are indicated at important points

Study Site

The Kootenai River is in the upper Columbia River Basin. The river originates in Kootenay National Park (US and Canadian spellings for Kootenai differ), BC, and flows south to Montana, turning northwest at the Libby Dam site (Fig. 1). As the river flows through the northeast corner of the Idaho Panhandle, it shifts to the north and enters Kootenay Lake, BC. The Kootenay River joins the Columbia River at Castlegar, BC. Our primary study reach for this investigation was the spawning area, from rkm 228.0 to 247.0, from the city of Bonners Ferry, ID, downstream (Paragamian et al., 2001) (Fig. 1).

Material and methods

River environment
Estimated flow at Bonners Ferry was calculated from gauge station readings at several major tributaries (below Libby Dam) and flow from Libby Dam (P. McGrane, USACE, pers. comm.). In 1994, flow in the Kootenai River at Banners Ferry, during white sturgeon migration and spawning, comprised primarily unregulated flow originating from tributaries below Libby Dam (local inflow). Some water from the dam was released to enhance spawning. After 1994, the Bonneville Power Administration (BPA) and USACE received a flow design from the USFWS in a biological opinion report on the

operation of federal dams in the Columbia Basin. This flow design was reviewed by the TMT and implemented to provide improved spawning and rearing conditions. Water temperatures were recorded from 1994 to 2000 at the US Geological Survey (USGS) gauging station at the US Highway 95 bridge in Bonners Ferry.

During 1999, flow mitigation was delayed and local inflow subsided, creating a delay in flow release until an adequate volume of 10 °C water could be released from Lake Koocanusa. The necessity for 10 °C water was based on observations of optimum temperature by Parsley and Beckman (1994) for white sturgeon in the Columbia River.

White Sturgeon egg collections and effort
We used artificial substrate mats (McCabe and Beckman, 1990) to document spawning from 1994 to 2000. We believe our sampling technique for eggs is supported by biologic characteristics of white sturgeon: they are broadcast spawners whose eggs are adhesive for a short time, and which sink immediately after expulsion (Stockley, 1981; Brannon, 1984; Cherr and Clark, 1985; Wang et al., 1985). Previous published studies of sturgeon egg sampling (Acipenseridae) also depended on these biologic characteristics (Kohlhorst, 1976; Buckley and Kynard, 1981; McCabe and Beckman, 1990; McCabe and
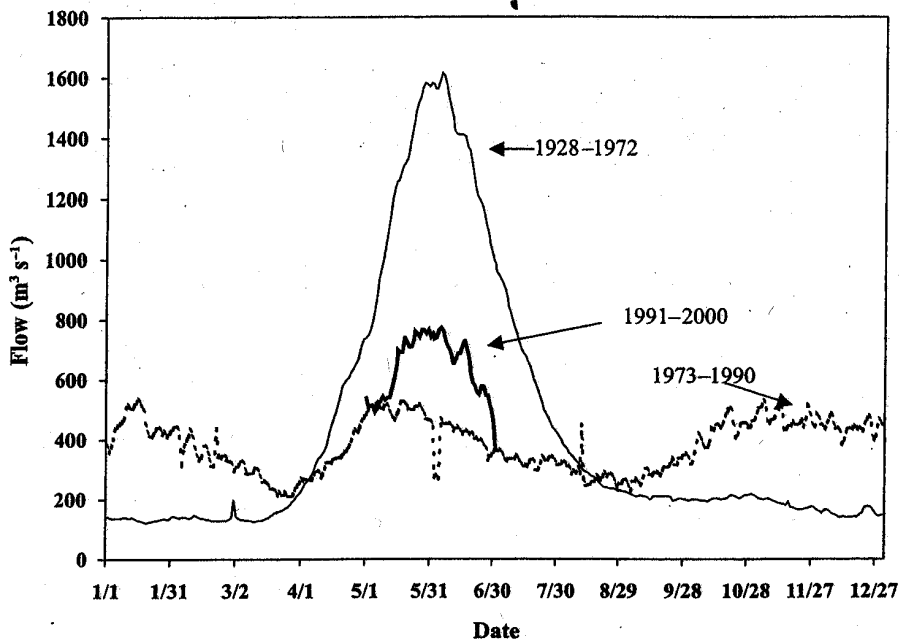
Fig. 2. Mean daily flow patterns in the Kootenai River at Bonners Ferry, Idaho, from 1928-1972 (pre-Libby Dam), 1973-1990 (post-Libby Dam), and 1991-2000 (post-Libby Dam with mitigated flows, May and June only)

Tracy, 1994; Parsley and Beckman, 1994; Marchant and Shutters, 1996; Hildebrand et al., 1999).

Several artificial substrate mats, herein `mats', and placement schemes were implemented early in our study to help identify white sturgeon spawning locations, including deployment within their staging reaches. 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 which included three staging areas (Paragamian and Kruse, 2001). In 1996, mats were distributed primarily in the main channel from rkm 228 to 247.7, as no eggs were collected near the river margins in the five previous years of sampling. From 1997-2000, mats were placed from rkm 227 to 247 and a standardized sampling regime was implemented 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 through the first week in July. Each season, we deployed 70-100 mats which were pulled and examined daily for presence of eggs. Eggs were removed from the mats and stored in labeled vials containing formalin or alcohol solution.

Estimated spawning dates
Embryonic age (h) of white sturgeon eggs were visually distinguishable with a dissection microscope at 120x and aged by using embryonic criteria developed by Beer (1981). Spawning dates (± 4 h) for the population were back-calculated from all viable eggs using an exponential function involving water temperature and embryonic development described by Beer (1981) and Wang et al. (1985). All eggs were viewed by at least two competent individuals to reach conformance. We used the age of white sturgeon eggs as a general index to estimate the date of expulsion and fertilization for the population, herein called an `event'.

Data analysis
Probability of a spawning event was calculated in 0.5 °C increments for mean daily temperature, and mean daily flows

by 1.0 m^3 s^{-1} increments recorded during spawning. We used the D'Agostino (D'Agostino, 1971a,b in Zar, 1984) procedure to examine the distributions for normality. This involves computation of a statistic called `D' as a powerful test for departure from normality with $n > 50$. The n observations in the sample are first arranged in ascending (or descending) order. Then, D is calculated as:

$$D = T / \sqrt{n^3 \ SS}$$

where,

$$SS = \text{sample sum of squares} = \sum x_i^2 - \sum x_i^2 / n$$

and,

$$T = \sum_{i=1}^{n} [i - (n + 1)/2] X_i$$

Then,

H_o (null hypothesis) if the sample came from a normal population and the

H_A (alternate hypothesis) if the sample did not come from a normal population.

A table (B.22 in Zar, 1984) is then consulted for the upper and lower critical values of D'Agostino's `D' at different significance levels, alpha, and for different sample sizes, n. If the calculated D is less than or equal to the first member of the pair of critical values, or greater than or equal to the second, then the null hypothesis of population normality is rejected.

Linear regression analysis was used to examine the relationship between the onset of spawning (the first day of spawning) with the mean daily temperature and mean daily flow.

Results

River environment
Average daily flow, hydrograph shape, and average daily temperatures varied considerably during May and June 1994-2000. Annual variations were created by differences in snow pack in the basin (79-130% of normal), volume of water
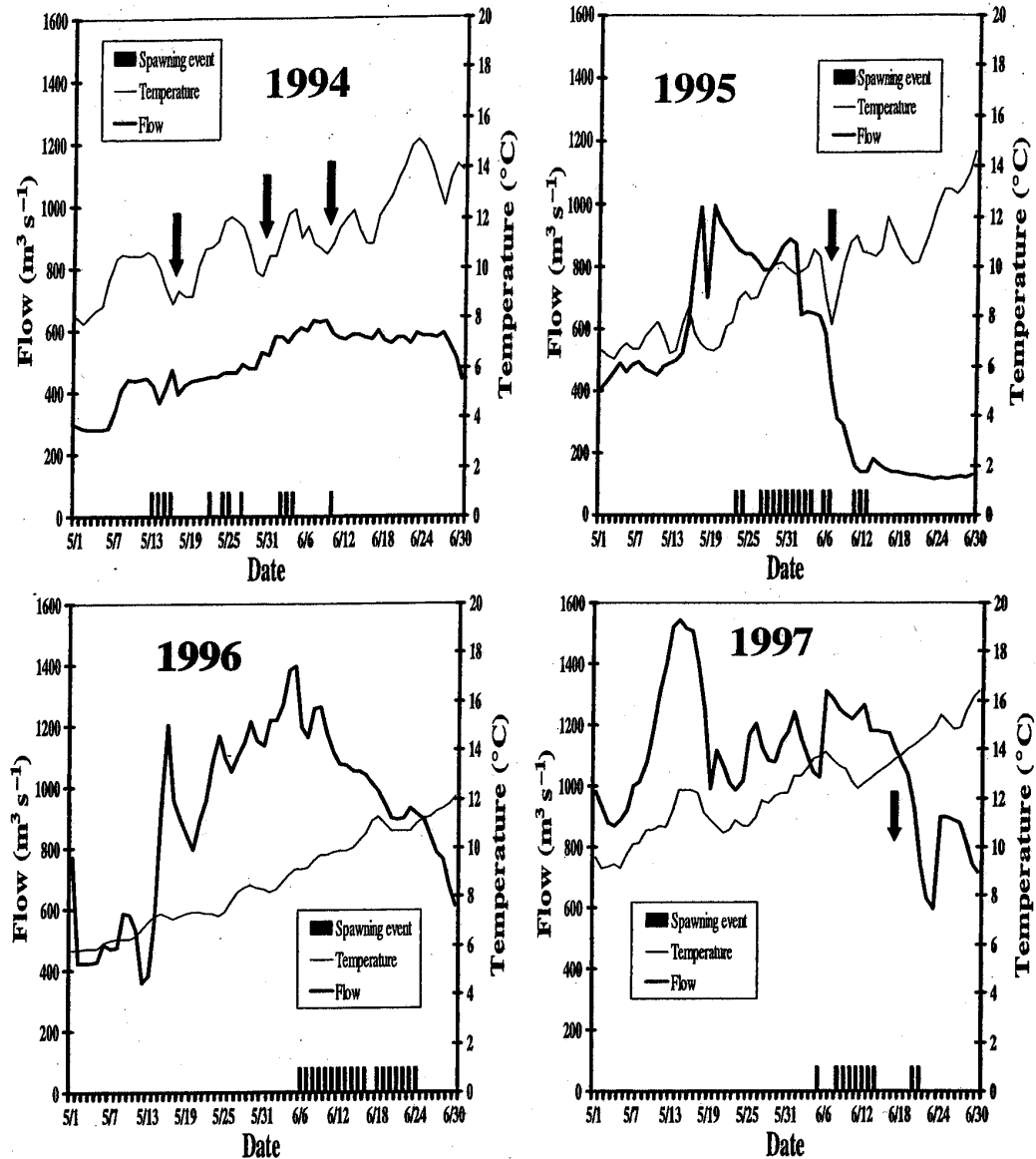
Fig. 3. Average daily temperature, average daily flow, and spawning events by date (vertical solid bar) for 1994, 1995, 1996, and 1997

stored in Lake Koocanusa, precipitation, thermal radiation, and water management decisions by the TMT. As a result, the request for the timing and magnitude of mitigated flows also varied (Figs 3 and 4). Prior to implementing the experimental flow mitigation (March-April), normal operation of Libby Dam usually allowed for base release of 113 $m^3 s^{-1}$ before the white sturgeon spawning period. Local inflow (flow from unregulated tributaries below Libby Dam) comprised the remainder of the total flow in the spawning reach downstream of Bonners Ferry. In 1994, mitigated flows for white sturgeon spawning started on June 1 and were maintained for 28 days (Figs 3 and 4). Temperature appeared to rise most rapidly in 1994, achieving 12 °C by late May. In 1995 flow mitigation was initiated on May 15 and continued through June 26. In 1996, local runoff was very high at Bonners Ferry (1,400 $m^3 s^{-1}$) and mitigation for spawning and rearing was not requested until July, after white sturgeon had spawned.

Temperatures in May 1996 ranged from about 6 to 8.5 °C, cooler than in all other years. Local runoff during our study was highest in 1997, bringing flow to 1526 $m^3 s^{-1}$ in early May; flow mitigation was not initiated until June 5, ending June 10 followed by a second pulse on June 12-13. In 1998 mitigated flows began on May 18 and continued through May 31; in 1999 flow was initiated on June 15 and continued through May 31; there were no mitigated flows for white sturgeon spawning in 2000. The USACE did not power peak during any of the white sturgeon spawning seasons.

Sampling effort, egg collections, viability, and ages

Sampling effort for the study reach ranged from 2401 mat-days in 1994 (1 mat-day is a 24-h set) to 4448 mat-days in 1996 (Table 1). High flows in 1997 impeded sampling because of debris transported into float lines and shifting sand
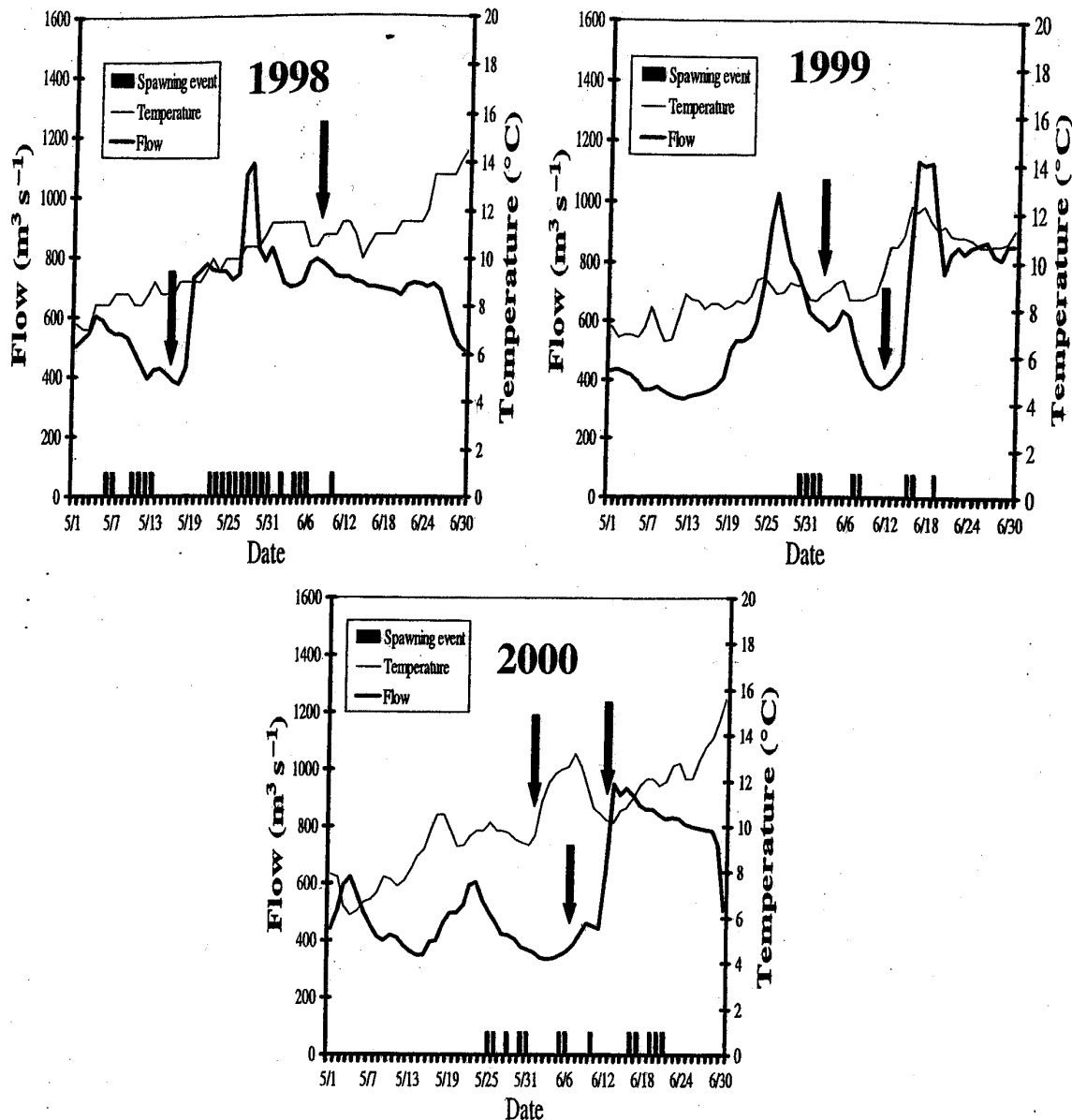
Fig. 4. Average daily temperature, average daily flow, and spawning events by date (vertical solid bar) for 1998, 1999, and 2000

Table 1 Summary of total mat effort (days), total number of eggs collected, number of viable eggs, range of egg stages, spawning events, and estimated spawning dates

Year	Total mat effort (days	Total number of eggs collected	Number of viable eggs (%)	Range of ages (h)	Number of estimated spawning events
1994	2401	213	135 (63%)	1-unknown	12
1995	3278	162	127 (78%)	1-108	16
1996	4448	349	256 (74%)	1-228	18
1997	4256	75	57 (77%)	1-336	10
1998	3759	483[a]	420[a] (87%)	1-293[b]	20
1999	3387	184	131 (71 %)	1-256	9
2000	2676	186	156 (84%)	1-48	13

[a]Ninety eggs were collected on six experimental sampling mats fitted with a drift net.
[b]A single white sturgeon larvae was .collected on a sampling mat but its age is not included.

burying the mats. A more detailed account is presented in Paragamian et al. (2001). Annual viability of white sturgeon eggs ranged from 63 to 87% (Table 1), while they ranged in age from 1 to 336 h (Table 1) with most eggs <48 h old.

Spawning events 1994-2000

Estimated dates of detected white sturgeon spawning events ranged from May 6 to June 24, with a median spawning date of

June 4. Latest times of spawning occurred in 1996 and 1997. Estimated total number of spawning events during each year ranged from nine to 20 (Table 1 and Figs 3 and 4).

Analysis of spawning events, temperature, and flow

Average daily temperature (in 0.5 °C increments) during the 1994-2000 spawning seasons ranged from 7.5 to 14 °C, with

the highest probability of spawning (48%) at the 9.5-9.9 °C interval (Fig. 5). Sixty-six percent of the spawning events took place between 9.5 and 12.5 °C. Distribution values for temperature were not normally distributed (D'Agostino $D = 0.2883$, $P = 0,05$). Values for the probability of spawning occurring at a given temperature were normally distributed (D'Agostino $D = 0.2741$, $P > 0.20$). White sturgeon spawned during rising water temperatures but
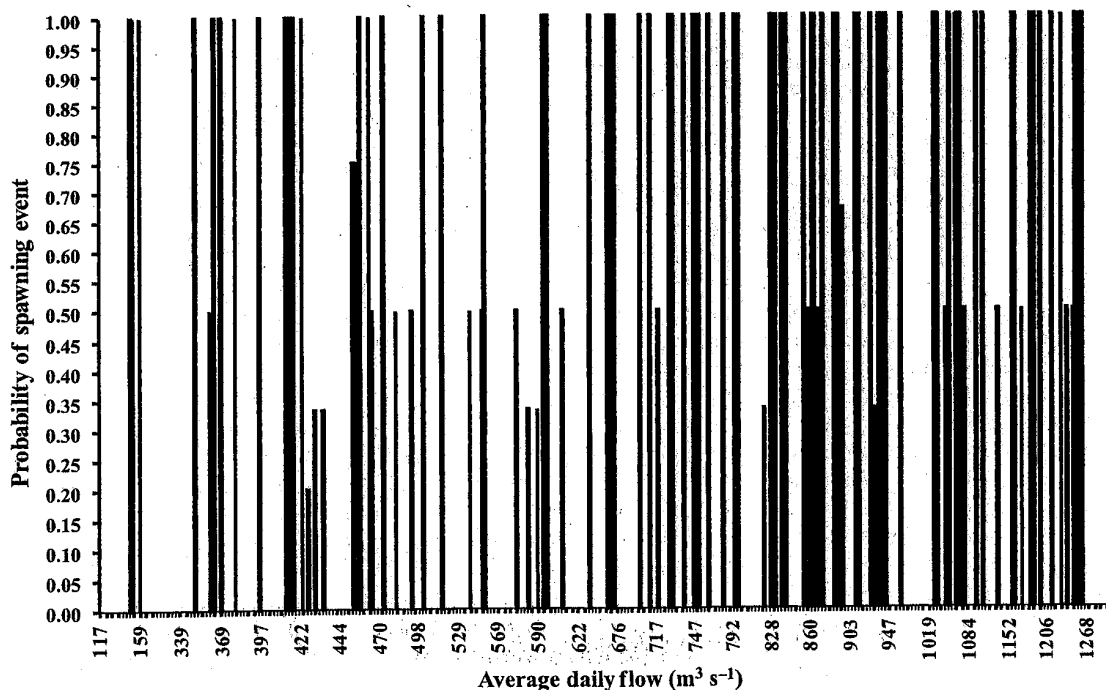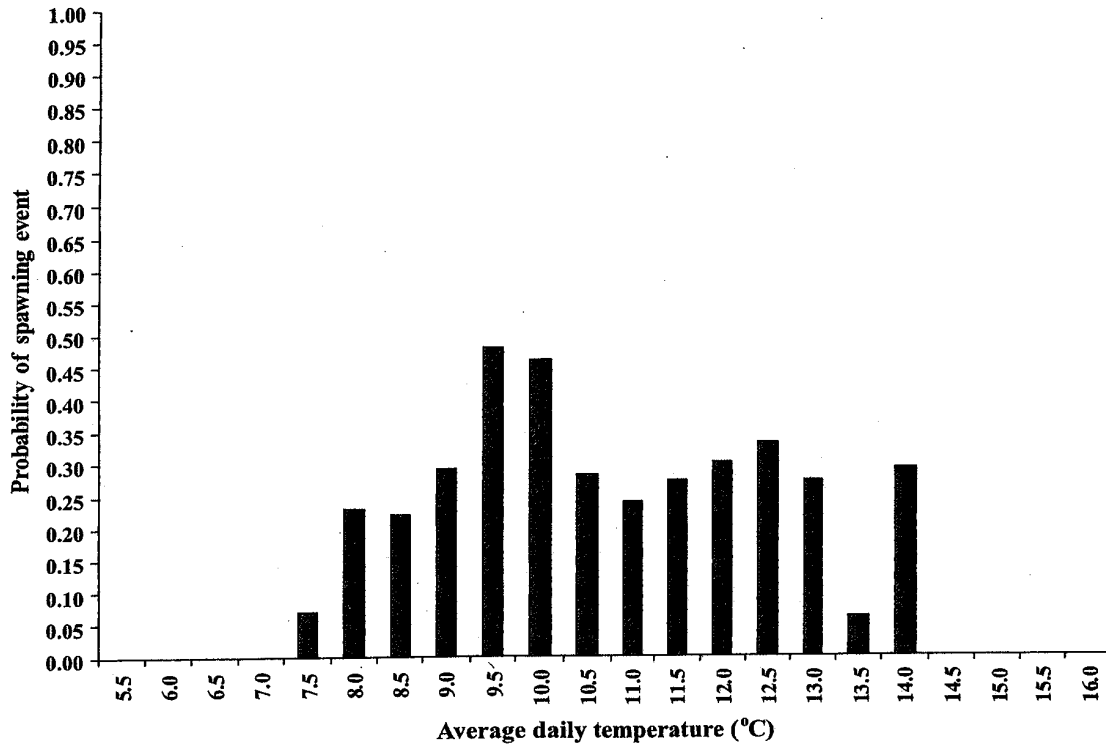

Fig. 5. Probability of Kootenai River white sturgeon spawning events by average daily temperature, 1994-2000 combined (upper panel. Probability of Kootenai River white sturgeon spawning events by average daily flow, 1994-2000 (lower panel)

ceased spawning when temperatures dropped by 0.8 °C or more.

Average daily flow for spawning events ranged from 141 to 1265 $m^3 s^{-1}$, with a high probability (100%) of spawning at several flow levels (Fig. 5). Spawning took place during increasing as well as decreasing flows (Figs 3 and 4), but there appeared to be a threshold between 350 and 400 $m^3 s^{-1}$ after which spawning seldom occurred. We calculated a 100% probability of a spawning event occurring at 3.5% of the recorded flow levels at or below 500 $m^3 s^{-1}$ and 11.5% of those at levels >500 but <1300 $m^3 s^{-1}$ (at 1 $m^3 s^{-1}$ increments). Sixty-three percent of the spawning events were recorded above 630 $m^3 s^{-1}$ while the mean flow during spawning episodes was 762 $m^3 s^{-1}$. Values for flow were normally distributed (D'Agostino $D = 0.2838$, $P > 0.20$), but values for the probability of a spawning event occurring at a given flow level were not (D'Agostino $D = 0.2212$, $P = 0.01$). We did not detect a statistical relationship between temperature and flow at the onset of sturgeon spawning with ($P > 0.43$).

We recorded 12 circumstances .from 1994 to 2000 when white sturgeon spawning ceased for three or more days (± 1 day of error) between the first and last events (Figs 3 and 4). In five cases spawning ceased when temperature had dropped ≥ 0.8 °C, two cases when mean daily flow alone dropped below 400 $m^3 s^{-1}$, one circumstance when flow dropped dramatically but still exceeded 400 $m^3 s^{-1}$, and two circumstances when both temperature and flow decreased simultaneously. There were two circumstances when spawning ceased, for which we have no explanation based on changes in temperature and/or flow.

Discussion

Each spring, Kootenai River white sturgeon adults complete their spawning journey by migrating from Kootenay Lake or down stream staging reaches to the spawning reach (Paragamian and Kruse, 2001). Males migrate first followed by the females, an average of 9 days later and usually associated with the spring freshet. The first records of spawning often occur within a few days of the arrival of females tagged with radio and sonic transmitters. Thus, it appears that the onset of white sturgeon spawning in the Kootenai River is dependent primarily on the arrival of females and may be predetermined based on migration temperature.

Water temperature is the most important environmental variable to predict migration of female white sturgeon to the spawning reach and for spawning (Paragamian and Kruse, 2001). Migration temperatures from 1991 to 1997 for 25 females ranged from 6.6 to 10.7 °C (Paragamian and Kruse, 2001), cooler than observed in other river systems. Wang et al. (1985) suggested that the optimum spawning temperature for white sturgeon was 14 °C, with an upper limit of 18 °C. Kohlhorst (1976) reported that peak spawning of white sturgeon in the Sacramento River was 14.5 °C. In the Columbia River, Parsley et al. (1993) found temperature to be the single most important variable to the onset of white sturgeon spawning. McCabe and Tracy (1994) found temperature to be one of the best predictors of the collection of recently spawned eggs on the Columbia River below Bonneville Dam.

After the onset of white sturgeon spawning, the temporal distribution of the detected spawning events appeared to be dependent on the relative stability of temperature and changes inflow. We found that the years or periods of spawning within a year with the most spawning events were associated with

temperatures that were stable, increasing or where changes were moderate (increases or decreases of $<\_ 0.7$ °C such as in 1995, 1996, and 1998). The most consistent year for recorded spawning events was 1996, when spawning occurred during 18 of 19 days. In that year, temperature gradually increased and flow was gradually ramping down at about 90 $m^3 s^{-1}$ day $^{-1}$. Asynchronous spawning occurred during years when there were several rapid decreases in temperature of up to 2 °C over a 2-day period or a rapid decrease in flow (1994, 1995, 1999, and 2000). However, we did monitor two rapid flow decreases during 1998, the year with the most recorded spawning events (20). On the Columbia River below the Bonneville Dam, during 1990 and 1991, McCabe and Tracy (1994) found that spawning occurred during the highest daily flows. Votinov and Kas'yanov (1978) believed the strongest year-classes of Siberian sturgeon *A. baerii* were associated with the years of highest flow in the Ob River.

The number of detected spawning events for sturgeon populations (Acipenseridae) appears to vary and is probably dependent on environmental conditions as well as the size of the adult stock and egg collection effort. In our study we recorded nine to 20 white sturgeon spawning events taking place within a range of 19-31 days. The number of spawning events in other regulated rivers ranged from as few as four in the Snake River, below Ice Harbor Dam (Counihan et al., 1999), to a range of 38-48 spawning events within 61-83 days on the Columbia River, below the Bonneville Dam (McCabe and Tracy, 1994). Buckley and Kynard (1985) reported that shortnose sturgeon A. *brevirostrum* in the Connecticut River spawned over a compressed period of 3-5 days below the Holyoke Dam, Connecticut; in 1 year of their study, they believed sturgeon did not spawn because environmental conditions were not right. Auer (1996) believed the response of lake sturgeon A. *fulvescens* to changes in a hydroelectric facility from a regulated river to `run of the river' were positive when time in the spawning reach was reduced from as long as 2 months to a period of 3 weeks.

We believe there may have been several sources of bias or error in our study. One possible source of error pertains to the level of accuracy in aging white sturgeon eggs, and back-calculation of the spawn date (± 4 h) (Beer, 1981; Wang et al., 1985). We attempted to reduce this error by the independent viewing of each egg by two or more persons experienced in aging developing eggs. A second possible source of bias is sampling error associated with mat placement and the possibility that we did not detect all spawning events. There was also the unexpected phenomenon that some unfertilized eggs can survive for several days and appear as recently fertilized eggs (Wang et al., 1985) and thereby provide false information on the spawning date (T. Counihan, USGS, Cook, Washington, pers. comm.).

The strength of our study was in the relationship of observed spawning events and corresponding temperature and flow. Our analysis suggests, flows for optimum white sturgeon, spawning in the Kootenai River should be held above 630 $m^3 s^{-1}$ and ideally at 1200 $m^3 s^{-1}$ with a temperature range of 9.5 to 12.5 °C (Paragamian et al., 2001). Given the available flows, we found no evidence to suggest a need for flows higher than 1300 $m^3 s^{-1}$ but there may be secondary benefits associated with higher flows. For example, higher flows may benefit white sturgeon eggs and larva by transporting sediments and resorting and exposing spawning gravel or by increasing the search area for predators. We recommend that mitigation flows begin as soon as local runoff begins to subside or when

female white sturgeon have moved to the spawning reach from staging areas, or both (Paragamian and Kruse, 2001). There has been little success at measuring recruitment of young white sturgeon from mitigated flow years, and the present level of recovery is still unknown (Paragamian et al., 1997). Providing proper temperature and flow mitigation is important to the recovery of Kootenai River white sturgeon but the issue of spawning habitat and survival of eggs and larvae is still unresolved and remains significant (Paragamian et al., 2001).

Acknowledgements

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Authors' address: Vaughn L. Paragamian, Idaho Department of Fish and Game 2750 Kathleen Avenue, Coeur d'Alene, ID 83815, USA.
E-mail: vparagam@idfg.state.id.us