Abstract.—Spawning and early life history of white sturgeon, *Acipenser transmontanus*, were studied in the lower Columbia River downstream from Bonneville Dam from 1988 through 1991. From white sturgeon egg collections, we determined that successful spawning occurred in all four years and that the estimated spawning period each year ranged from 38 to 48 days. The spawning period extended from late April or early May through late June or early July of each year. Spawning occurred primarily in the fast-flowing section of the river downstream from Bonneville Dam, at water temperatures ranging from 10 to 19°C. Freshly fertilized white sturgeon eggs were collected at turbidities ranging from 2.2 to 11.5 nephelometric turbidity units (ntu), near-bottom velocities ranging from 0.6 to 2.4 m/s, mean water column velocities ranging from 1.0 to 2.8 m/s, and depths ranging from 3 to 23 m. Bottom substrate in the river section where freshly fertilized eggs were most abundant was primarily cobble and boulder. White sturgeon larvae were collected from river kilometer (rkm) 45 to rkm 232, suggesting wide dispersal after hatching. Larvae were collected as far downstream as the upper end of the Columbia River estuary, which is a freshwater environment. Young-of-the-year (YOY) white sturgeon were first captured in late June, less than two months after spawning was estimated to have begun. Growth was rapid during the first summer; YOY white sturgeon reached a minimum mean total length of 176 mm and a minimum mean weight of 30 g by the end of September. Young-of-the-year white sturgeon were more abundant in deeper water (mean minimum depth ≥12.5 m) of the lower Columbia River. The results indicate that a large area of the lower Columbia River is used by white sturgeon at different life history stages.

Manuscript accepted 28 February 1994.
Fishery Bulletin 92:760–772.

Spawning and early life history of white sturgeon, *Acipenser transmontanus*, in the lower Columbia River

George T. McCabe Jr.
Coastal Zone and Estuarine Studies Division, Northwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2725 Montlake Blvd. East, Seattle, Washington 98112-2097

Charles A. Tracy
Columbia River Fisheries Laboratory, Washington Department of Fish and Wildlife
P.O. Box 999, Battle Ground, Washington 98604

White sturgeon, *Acipenser transmontanus*, is the largest of all North American sturgeon species and is found along the west coast of North America from the Aleutian Islands, Alaska, to Monterey, California (Scott and Crossman, 1973). Although this species is generally anadromous (Scott and Crossman, 1973), some populations in the Columbia River Basin are landlocked because of dam construction or natural barriers (Cochnauer et al., 1985; Beamesderfer et al.[1]).

Historically, white sturgeon were abundant in the Columbia River (Oregon and Washington) and in the late 1800's supported an intense commercial fishery. Commercial catches peaked in 1892, when more than 2.4 million kg were landed (Craig and Hacker, 1940). After 1892, catches declined, and by 1899 the annual catch was less than 33,250 kg. Annual catches during the early 1900's were less than 104,930 kg (Craig and Hacker, 1940).

White sturgeon populations in the Columbia River, particularly the one downstream from Bonneville Dam (the lowest dam at river kilometer [rkm] 234), have recovered sufficiently from the overfishing to support important recreational and commercial fisheries. The population of white sturgeon in the lower Columbia River, which extends from the mouth of the river to Bonneville Dam, is one of the largest in the world. From 1984 through 1988, the combined recreational and commercial catch in this area was at least 50,000 fish annually (Wash. Dep. Fisheries and Oregon Dep. Fish and Wildlife[2]). During 1992, estimated catches of white sturgeon for recreational and commercial fisheries were 40,100 and 6,200 fish, respectively (Melcher and King[3]). Presently, white sturgeon is the principal recreational fish in the Columbia River downstream from Bonneville Dam (Melcher and King[3]).

[1] Beamesderfer, R. C., T. A. Rien, C. A. Foster, and A. L. Ashenfelter. 1990. Report A. *In* A. A. Nigro (ed.), Status and habitat requirements of white sturgeon populations in the Columbia River downstream from McNary Dam, p. 6–37. Ann. Rep. to Bonneville Power Admin. (Project 86-50) by Oreg. Dep. Fish Wildl., Wash. Dep. Fish., Natl. Mar. Fish. Serv., and U.S. Fish Wildl. Serv. Avail. Bonneville Power Admin., P.O. Box 3621, Portland, OR 97208.

[2] Washington Department of Fisheries and Oregon Department of Fish and Wildlife. 1992. Status report—Columbia River fish runs and fisheries, 1938–91, 224 p. Avail. Wash. Dep. Fish., P.O. Box 999, Battle Ground, WA 98604.

[3] Melcher, C. E., and S. D. King. 1993. The 1992 lower Columbia River and Buoy 10 recreational fisheries, 77 p. Oregon Dep. Fish Wildl., 17330 S.E. Evelyn St., Clackamas, OR 97015.

Although white sturgeon supports important fisheries in the Columbia River and other rivers within its range, little is known about the spawning characteristics and early life history of this long-lived species. Using larval collections, Stevens and Miller (1970) described the distribution of white or green, *A. medirostris,* sturgeon larvae, or both, in California's Sacramento-San Joaquin River system, and Kohlhorst (1976) described sturgeon spawning in the Sacramento River. Parsley et al. (1993) described spawning and rearing habitats of white sturgeon in the Columbia River downstream from McNary Dam; however, important specific information about spawning and early life history of white sturgeon in the Columbia River downstream from Bonneville Dam was not presented.

From 1988 through 1991, we studied spawning characteristics and early life history of white sturgeon in the lower Columbia River. Primary goals of the study were 1) to define where and when spawning occurred and 2) to assess the environmental conditions at the time of spawning. Additional goals were to determine larval distribution and habitat use by young-of-the-year (YOY) white sturgeon.

Methods

Egg and larval sampling

From 1988 through 1991, white sturgeon eggs and larvae were collected in the Columbia River downstream from Bonneville Dam. The collection period varied among years; however, in all years, it extended from at least April through early July. Generally, samples were taken weekly during this period. A D-shaped plankton net was used to collect white sturgeon eggs and larvae. This net was 0.8 m wide at the bottom of the mouth opening, 0.5 m high, and constructed of 7.9-mesh/cm nylon marquisette netting. Depending on water velocity, two to six lead weights (4.5 or 9.1 kg each) were attached to the net frame to hold the net on the river bottom. A digital flow meter (General Oceanics Model 2030) was suspended in the mouth of the net to estimate the volume of water sampled. Typically, two plankton nets were fished simultaneously for about 30 minutes from an anchored 12.2-m research vessel. When water velocities at 0.2 of the total depth were greater than 2 m/s and other adverse sampling conditions were present, only one plankton net was fished, often for one hour.

Artificial substrates constructed of latex-coated animal hair also were used to collect white sturgeon eggs (McCabe and Beckman, 1990). Each artificial substrate, which was 76 × 91 cm, was enclosed in an angle-iron frame. The substrate and frame were held in place on the bottom with a three-fluke anchor similar to a grapnel. A buoy line was attached to the anchor to allow retrieval of the substrate, frame, and anchor. Artificial substrates were generally retrieved and examined weekly for eggs.

In 1990 and 1991, a 3.0-m beam trawl was used weekly or biweekly in late June, July, and August to collect white sturgeon larvae and YOY. The estimated fishing width of the trawl was 2.7 m and the height was 0.5 m. A 1.59-mm knotless nylon liner was inserted into the body of the net. The beam trawl was towed slowly upstream along the bottom for periods ranging from 2 to 20 minutes.

White sturgeon eggs and larvae were initially preserved in an approximately 4% buffered formaldehyde solution. After the eggs and larvae were processed in the laboratory, they were transferred to a 20% methanol solution. Processing of the eggs and larvae was done within 60 days after collection.

White sturgeon egg or larval sampling was conducted at various sites in the lower Columbia River from rkm 29 to 234 (Table 1, Fig. 1). Following exploratory research conducted in 1987, we decided to concentrate egg and larval sampling with stationary gear (plankton nets and artificial substrates) between rkm 172 and 234. We selected a site at rkm 230, used in previous research for monitoring white sturgeon spawning, for the most frequent egg sampling. We call this the index site.

In 1988, a 12-hour collection with a plankton net was made at the index site to determine whether catches of white sturgeon eggs and larvae changed during different light conditions. The study began at 1843 hours on 25 May and ended at 0623 hours on 26 May. Normally, one plankton net was fished for one hour during each sampling effort; 11 sampling efforts were made.

Young-of-the-year sampling

A 7.9-m (headrope length) semiballoon shrimp trawl was used to collect juvenile white sturgeon, including YOY, from 1988 through 1991. Mesh size in the trawl was 38 mm (stretched) in the body; a 10-mm mesh liner was inserted in the cod end. Trawling efforts with the shrimp trawl were normally five minutes in duration in an upstream direction, beginning when the trawl and the proper amount of cable were deployed, and ending five minutes later. Trawl speed over the bottom was usually 3 to 5 km/hour. In 1990 and 1991, a 3.0-m beam trawl was also used to collect YOY white sturgeon (see Egg and Larval Sampling section). Using a radar range-finder, we estimated the distance fished during each sampling effort. Beam trawl speed over the bottom was usually 1 to 3 km/hour.

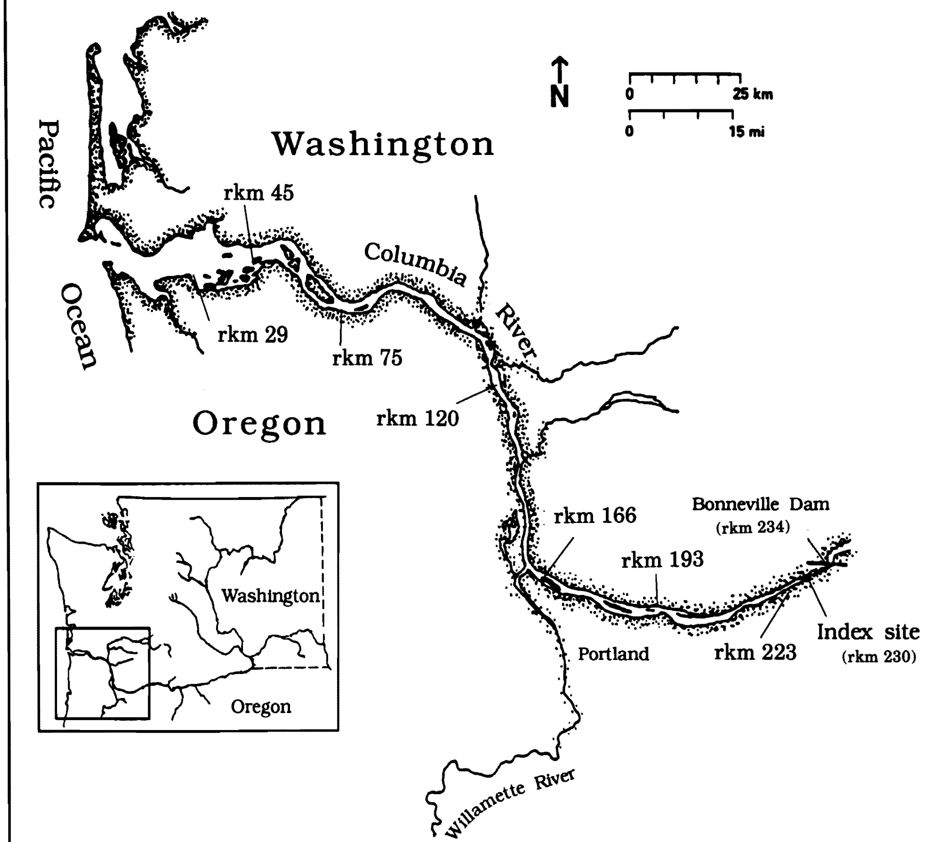

Figure 1

Location of the white sturgeon, *Acipenser transmontanus,* study area in the lower Columbia River, 1988–91.

Trawling was conducted from late March or early April through September or October of each year. In 1989, a limited amount of sampling was conducted in early November. Sampling stations were selected to determine the range of habitat used by juvenile white sturgeon and extended from rkm 29 to 218 (Table 1). Trawling effort and geographic range of sampling varied among years owing to limited personnel and gear (Table 1). In 1988 and 1989, more trawling effort was concentrated in the river upstream from rkm 120. However, in 1990 and 1991, much more trawling was done in the river between rkm 45 and 120 than in previous years. White sturgeon captured in bottom trawls were measured (total length) and weighed (g).

On 31 July and 1 August 1990, 14 trawling efforts (7.9-m shrimp trawl) were undertaken from 1155 through 0800 hours at rkm 75 to determine whether catches of juvenile white sturgeon, particularly YOY, increased during hours of darkness.

Physical conditions

Selected physical parameters were measured in conjunction with biological sampling: minimum and maximum bottom depth (m); bottom water temperature (°C); bottom water turbidity (ntu); and water velocities at 0.2 of the total depth, 0.8 of the total depth, and about 0.6 m above the bottom. By averaging water velocities measured at 0.2 and 0.8 of the total depth, we calculated a mean water column velocity (Buchanan and Somers, 1969). Water velocities were measured only during egg and larval sampling. Depth was measured with electronic depth sounders, and velocity with a Gurley current meter attached to a 45.4-kg lead fish. A Van-Dorn water bottle was used to collect water samples just above the bottom. The water temperature of each sample was measured immediately after collection, and a subsample of water was removed and placed in a glass bottle. The turbidity of the subsample was determined in the laboratory with a Hach Model 2100A Turbidimeter.

Substrate type was determined from bottom samples collected with a 0.1-m^2 Van Veen grab sampler. In addition, a substrate sample was collected at rkm 230 (index site) by scuba divers. Particle size was defined following the classifications presented in Parsley et al. (1993).

Table 1

Numbers of sampling efforts for white sturgeon, *Acipenser transmontanus*, eggs, larvae, and young of the year in the lower Columbia River, 1988–91. When two plankton nets were fished simultaneously, the data were combined and considered as one sampling effort. Location is shown in river kilometers (rkm).

Year and location	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Plankton net									
1988									
rkm 172–228	0	0	8	17	1	0	0	0	26
rkm 229–230	1	2	16	5	2	1	0	0	27
rkm 231–233	1	3	6	1	0	0	0	0	11
1989									
rkm 153–171	0	0	2	0	0	0	0	0	2
rkm 172–228	0	0	18	16	5	0	0	0	39
rkm 229–230	1	2	4	5	3	1	0	0	16
rkm 231–233	0	0	1	0	0	0	0	0	1
1990									
rkm 112–171	0	0	0	1	0	0	0	0	1
rkm 172–228	0	0	29	10	3	0	0	0	42
rkm 229–230	0	5	5	4	3	0	0	0	17
rkm 231–233	0	1	2	2	0	0	0	0	5
1991									
rkm 193–228	0	1	13	8	5	0	0	0	27
rkm 229–230	0	4	4	7	6	0	0	0	21
rkm 231–233	0	0	0	0	0	0	0	0	0
Artificial substrate									
1988									
rkm 197–228	0	0	3	1	0	0	0	0	4
rkm 229–230	0	0	5	1	2	0	0	0	8
rkm 231–234	0	0	5	6	0	0	0	0	11
1989									
rkm 220–228	0	0	2	3	0	0	0	0	5
rkm 229–230	0	1	0	0	0	0	0	0	1
rkm 231–234	0	0	12	6	0	0	0	0	18
1990									
rkm 229–230	0	3	5	0	0	0	0	0	8
rkm 231–234	0	0	9	4	2	0	0	0	15
1991									
rkm 229–230	0	2	3	3	3	0	0	0	11
rkm 231–234	0	0	6	4	0	0	0	0	10
Beam trawl									
1990									
rkm 29–120	0	0	0	15	11	5	0	0	31
rkm 121–212	0	0	0	2	12	2	0	0	16
1991									
rkm 44–120	0	0	1	9	19	4	0	0	33
rkm 121–218	0	0	1	12	9	4	0	0	26
Shrimp trawl									
1988									
rkm 46–120	4	3	3	6	6	3	4	3	32
rkm 121–211	19	17	10	31	40	56	6	39	218
1989									
rkm 38–120	3	3	3	6	18	11	7	30[1]	81
rkm 121–218	17	24	34	40	50	67	25	49	306
1990									
rkm 45–120	0	42	29	24	27	37	13	32	204
rkm 121–212	0	18	21	0	19	5	4	23	90
1991									
rkm 45–120	0	33	29	16	15	30	31	0	154
rkm 121–212	0	24	2	20	21	1	25	0	93

[1] Includes eight sampling efforts conducted in November.

Data analyses

The developmental stages of white sturgeon eggs were determined from descriptions by Beer (1981). Timing of spawning was estimated from developmental stages of eggs and temperature-egg developmental data from Wang et al. (1985). Water temperature at the time of egg collection was used in making the estimates, and a daily index of spawning activity was calculated from these estimated spawning dates. The index of spawning activity was treated as a dichotomous variable: spawning occurred or did not occur on a particular day.

Stepwise regression (Ryan et al., 1985) was used to determine relationships between the abundance of freshly fertilized (stage 2) white sturgeon eggs collected in plankton nets at the index site and physical parameters, including water temperature, turbidity, mean water column velocity, near-bottom water velocity, and Bonneville Dam discharge. Stage-2 eggs were assumed to be approximately three hours old or less (Beer, 1981). Bonneville Dam discharge for these comparisons was estimated by averaging hourly discharge at the time of sampling with discharges during the three hours prior to sampling. White sturgeon egg abundance and all physical parameters were tested for normality. Egg abundance (eggs/1,000 m^3) and turbidity failed the test for normality; both were normalized by using a $\log_{10}$ transformation. Data collected just prior to, during, and just after the spawning period were used for the regression analyses. Transformed egg abundance was also plotted against each of the above physical parameters to investigate the possibility of nonlinear relationships. The plots suggested that the relationship between egg abundance and water temperature may be nonlinear; therefore, we used second-degree polynomial (quadratic) regression (Ryan et al., 1985) to examine this relationship.

For data analysis, YOY white sturgeon were separated from older juvenile sturgeon by length. A YOY was defined as being between 25 and 325 mm total length and less than one year old. Sturgeon shorter than 25 mm were considered larvae. A white sturgeon's birth date was assumed to be 1 January, although in reality the birth date was generally later in the year.

Results

Eggs

The number of white sturgeon eggs collected from 1988 through 1991 ranged from 1,404 in 1988 to 2,785 in 1990 (Table 2); however, sampling effort was not equal each year. The percent of white sturgeon eggs collected in plankton nets, as opposed to artificial substrates, also varied annually, ranging from 37% in 1991 to 87% in 1989. Virtually all white sturgeon eggs were collected in the 11-km section of river extending from rkm 223 to 234, immediately downstream from Bonneville Dam. In both 1990 and 1991, four white sturgeon eggs were collected at rkm 193. In all years, 4% or less of white sturgeon eggs collected in plankton nets were infected with fungus, indicating infertile or dead eggs.

From the spawning index, which was derived from back calculations by using the developmental stages of all eggs, we estimated that spawning occurred on 38 days in 1988, from 22 April to 22 June, and that 58% of the spawning days were in May (Fig. 2). In 1989, spawning occurred on an estimated 43 days, from 22 April to 2 July, and 53% of the spawning days were in May. In 1990, spawning was estimated to have occurred on at least 48 days, from 23 April to 14 July, and 46% of the spawning days were in May. Finally, for 1991, we estimated that spawning occurred on 39 days, from 5 May to 14 July, and 56% of the spawning days were in May.

Water temperatures measured at Bonneville Dam and at sampling sites during the spawning period varied annually (Fig. 2). Water temperatures at Bonneville Dam sometimes differed by about 1°C from those at egg collection sites. From 1988 to 1991, white sturgeon spawned at water temperatures ranging from 10 to 19°C (Bonneville Dam or sampling site temperatures).

Bonneville Dam discharge (mean hourly discharge by day) also varied annually (Fig. 2). The highest daily flows through Bonneville Dam during the sampling periods occurred during the spawning periods in 1990 and 1991. Combining data from all years, we concluded that spawning occurred on days with mean discharges ranging from 3,399 to 10,505 m^3/s.

During the 4-year study, stage-2 eggs were collected at temperatures from 10 to 18°C, turbidities from 2.2 to 11.5 ntu, near-bottom velocities from 0.6 to 2.4 m/s, mean water column velocities from 1.0 to 2.8 m/s, and depths from 3 to 23 m.

White sturgeon spawned primarily in the area upstream from rkm 222. Virtually all stage-2 eggs were collected between rkm 223 and rkm 234 (about 600 m downstream from the spillways at Bonneville Dam). Small numbers of stage-2 eggs were collected at rkm 193—three in 1990 and one in 1991. Exact spawning locations could not be determined because it was not possible to measure the distance that white sturgeon eggs were carried by the river current immediately after spawning. In addition, at least some white sturgeon eggs, which adhere to bottom substrate, were dislodged by water currents and carried downstream.

Substrate in the river section, where stage-2 eggs were most abundant, was primarily cobble and boulder. We are not sure of the composition of the substrate near rkm 193; however, there are small rocky islands in the area, and on occasion large amounts of sand were collected in the plankton net. In addition, there is a rocky reef several kilometers upstream from this sampling site.

At the index site, stage-2 eggs were collected over a range of environmental conditions from 1988 through 1991 (Table 3). Water temperatures ranged from 10 to 18°C, bottom water turbidities from 2.2 to

Table 2

Numbers of white sturgeon, *Acipenser transmontanus,* eggs and larvae collected in the Columbia River downstream from Bonneville Dam, 1988–91. Plankton nets and artificial substrates were used to collect eggs; plankton nets and a 3.0-m beam trawl (in 1990 and 1991) were used to collect larvae. Area refers to the geographic range (in river kilometers [rkm]) over which eggs or larvae were collected. Fungus-infected eggs collected in plankton nets are shown in parentheses and are included in the numbers reported for the nets. A dash (—) indicates that no sampling was conducted.

	Eggs			Larvae		
Sampling period	Area (rkm)	Net	Substrate	Area (rkm)	Net	Trawl
1988						
15–30 Apr	230–231	19	—		0	—
1–15 May	228–233	163 (1)	46	228–230	11	—
16–31 May	230–233	405 (10)	539	193–231	71	—
1–15 Jun	226–234	112 (5)	84	181–230	5	—
16–30 Jun	226–230	20 (1)	16	226	3	—
1–15 Jul		0	0		0	—
16–31 Jul		0	0		0	—
Total		719 (17)	685		90	—
1989						
15–30 Apr	230	385	47		0	—
1–15 May	224–234	275 (1)	37	174–232	19	—
16–31 May	224–234	703 (6)	212	181–230	39	—
1–15 Jun	222–234	640 (23)	9	193–230	64	—
16–30 Jun	226–230	13 (3)	0	181–230	13	—
1–15 Jul	226	2 (1)	—		0	—
16–31 Jul		0	—		0	—
Total		2,018 (34)	305		135	
1990						
15–30 Apr	230–231	386	258		0	—
1–15 May	223–234	904 (38)	153	223–232	34	—
16–31 May	193–234	187 (7)	275	181–230	34	—
1–15 Jun	224–234	210 (8)	260	112–230	33	—
16–30 Jun	224–230	109 (20)	0	45–230	41	12
1–15 Jul	226–234	8	35	67–226	1	25
16–31 Jul		0	0	127–230	9	1
Total		1,804 (73)	981		152	38
1991						
15–30 Apr		0	0		0	—
1–15 May	224–234	129 (1)	589		0	—
16–31 May	193–234	303 (3)	265	193–230	28	0
1–15 Jun	226–234	46 (7)	205	193–230	17	—
16–30 Jun	224–234	227 (1)	164	45–230	45	33
1–15 Jul	193–230	30 (2)	50	98–230	37	18
16–31 Jul		0	0		0	0
Total		735 (14)	1,273		127	51

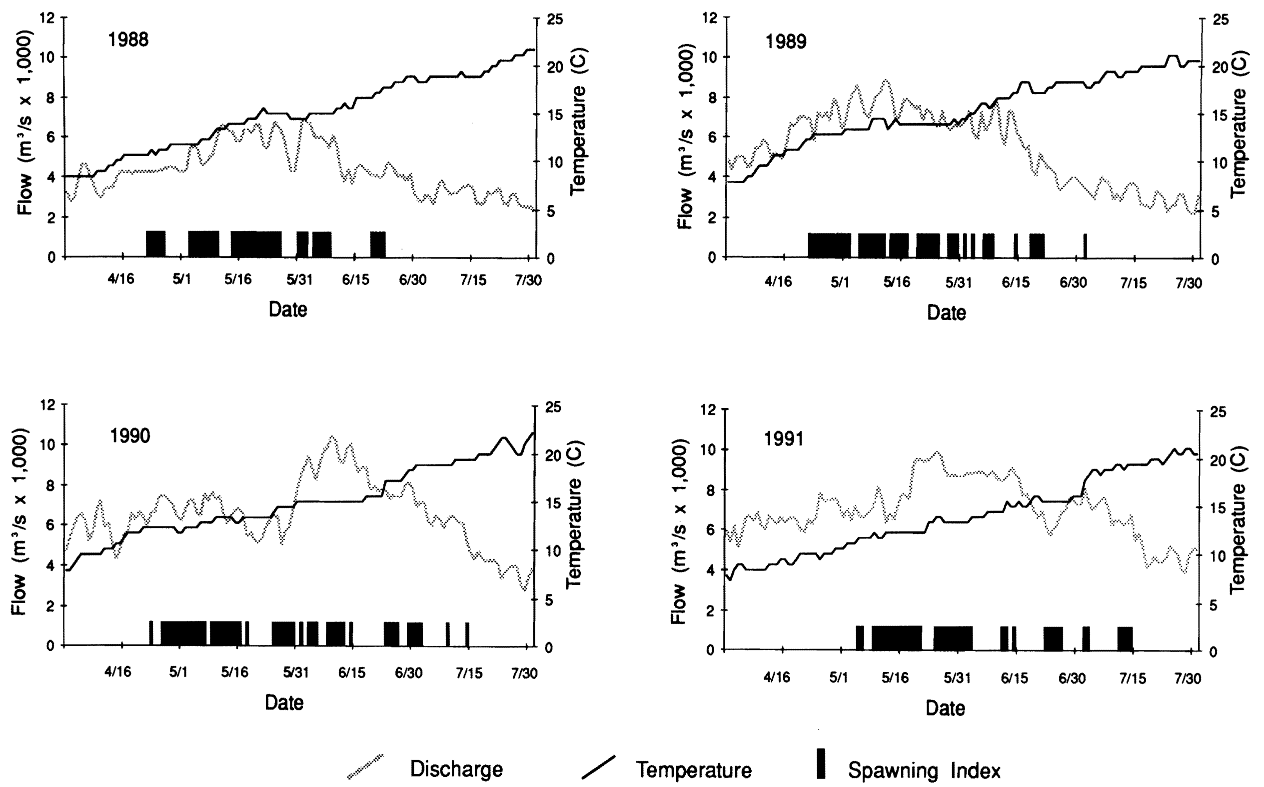

Figure 2

Water temperatures (°C) and Bonneville Dam discharges (mean hourly water discharges by day) from 1 April through 31 July (1988–91); discharge is shown as $m^3/s \times 1{,}000$. Water temperatures were measured at Bonneville Dam. The spawning index shows the days on which we estimated that white sturgeon spawned.

11.5 ntu, near-bottom water velocities from 1.0 to 2.1 m/s, and mean water column velocities from 1.5 to 2.6 m/s. Estimated Bonneville Dam discharges at the index site during spawning ranged from 3,890 to 9,600 m^3/s. In all years, the highest egg catches occurred during late April or May.

Results from stepwise regression indicated that water temperature and mean water column velocity together were the best predictors of stage-2 egg collections at the index site; however, they explained only 27.1% of the variation in the egg collections. The regression equation was $\log_{10}$ (number of eggs plus one/1,000 m^3) = 1.01 – 0.110 (water temperature) + 0.637 (mean water column velocity); F = 7.99 and P = 0.001. Bottom water turbidity was an important predictor in the first three steps of the stepwise regression, but dropped out in the fourth and final step. If a high turbidity value and accompanying zero egg catch (18 April 1989; see Table 3) are removed from the stepwise regression, the results change. Excluding the turbidity data for 18 April 1989, stepwise regression indicated that water temperature and turbidity together were the best predictors of stage-2 egg collections at the index site. The regression equation was $\log_{10}$ (number of eggs plus one/1,000 m^3) = 0.937 – 0.0857 (water temperature) + 1.70 ($\log_{10}$ turbidity); F=11.65, P=0.000, and r^2=35.7%. Second-degree polynomial regression indicated a significant relationship between stage-2 egg collections and water temperature (F=8.70, P=0.001, and r^2=28.8%). The regression equation was $\log_{10}$ (number of eggs plus one/1,000 m^3) = –4.44 + 0.846 (water temperature) – 0.0326 (water temperature^2).

Catches of freshly fertilized white sturgeon eggs during the 12-hour collection at the index site fluctuated; catches ranged from 0.0 to 72.2 eggs/1,000 m^3 (Table 4). On the basis of collections of freshly fertilized eggs during the 12-hour collection and daylight collections during the 4 years, it appears that adult white sturgeon spawn throughout the 24-hour day.

Larvae

White sturgeon larvae were collected from rkm 45 to rkm 232 in the lower Columbia River from 1988 through 1991 (Table 2), suggesting wide dispersal

Table 3

White sturgeon, *Acipenser transmontanus,* egg (freshly fertilized) catches and accompanying physical measurements for the index site near rkm 230 in the lower Columbia River, 1988–91. Water temperatures (on site), turbidities, and bottom velocities were measured just above the bottom; Bonneville Dam flow was the average of the hourly discharges at the time of sampling and during the three hours prior to sampling.

Date	Temperature (°C)	Turbidity (ntu)	Velocity (m/s)		Dam flow ($m^3/s \times 1,000$)	No. eggs	Eggs/ 1,000 m^3
			Bottom	Mean column			
1988							
25 Apr	10	4.5	1.0	1.5	3.89	3	1.7
5 May	11	6.4	1.4	1.8	5.14	24	19.5
10 May	13	6.0	1.0	1.6	5.95	80	54.1
18 May	13	6.0	1.2	1.6	6.24	4	2.1
23 May	14	5.4	1.2	2.1	5.59	10	6.4
2 Jun	14	6.0	1.4	2.3	6.51	18	10.3
8 Jun	14	3.5	1.4	2.0	5.43	19	12.4
16 Jun	16	3.5	1.1	1.8	4.50	0	0.0
20 Jun	16	3.2	1.1	1.5	4.17	9	6.9
29 Jun	17	3.1	1.0	1.6	3.90	0	0.0
1989							
18 Apr	10	12.0	1.5	1.9	6.46	0	0.0
27 Apr	12	10.0	1.5	2.2	7.11	348	219.9
1 May	12	7.5	1.7	2.0	6.96	17	10.3
10 May	13	7.5	—	2.4	7.89	70	40.9
17 May	14	9.2	1.6	2.3	8.30	525	284.5
24 May	14	5.9	1.4	2.2	6.82	18	10.8
1 Jun	14	5.4	1.6	2.2	6.80	1	0.6
8 Jun	16	5.3	2.0	2.6	7.66	99	58.3
15 Jun	17	3.4	1.5	2.2	5.91	0	0.0
21 Jun	17	3.7	1.0	1.9	4.60	0	0.0
28 Jun	18	3.3	1.1	1.6	3.98	0	0.0
6 Jul	19	3.5	1.0	1.6	3.72	0	0.0
1990							
23 Apr	11	3.0	1.1	1.5	6.61	0	0.0
30 Apr	11	3.5	1.1	2.2	7.20	225	133.2
7 May	12	3.9	1.7	2.6	7.57	32	14.8
14 May	12	3.7	1.8	2.3	7.03	292	166.9
22 May	13	3.0	1.1	1.7	4.69	0	0.0
29 May	14	3.0	1.4	2.3	5.90	39	25.6
5 Jun	15	3.4	1.7	2.5	8.32	19	10.0
11 Jun	15	6.5	1.5	2.4	9.07	23	12.9
18 Jun	15	5.6	2.1	2.7	9.01	0	0.0
25 Jun	17	3.7	1.7	2.5	7.52	2	1.1
2 Jul	18	2.2	1.2	2.1	6.71	1	0.5
9 Jul	19	1.9	1.1	2.2	5.56	0	0.0
18 Jul	20	2.0	1.1	1.8	4.25	0	0.0
1991							
30 Apr	10	3.6	1.3	2.1	7.67	0	0.0
6 May	11	3.0	1.3	2.1	6.80	2	1.2
14 May	12	4.2	1.4	2.0	6.81	98	56.5
20 May	12	5.3	2.1	2.6	9.60	15	14.4
29 May	14	6.3	1.5	2.6	8.79	2	1.4
3 Jun	14	11.5	2.1	2.6	9.10	11	7.1
19 Jun	16	4.2	1.4	2.5	7.39	0	0.0
26 Jun	15	3.7	1.1	2.2	7.36	12	7.5
3 Jul	18	4.3	1.7	2.4	7.38	9	5.2
9 Jul	19	2.8	1.2	1.6	5.55	0	0.0
15 Jul	19	3.5	1.0	1.8	5.40	0	0.0

Table 4

Summary of white sturgeon, *Acipenser transmontanus*, egg (freshly fertilized) and larval collections during a 12-h study at the index site near rkm 230 in the lower Columbia River. Sampling was done from 1843 hours on 25 May to 0623 hours on 26 May 1988 with a plankton net. Bonneville Dam flow was the average of hourly discharges at the time of sampling and during the 3 hours prior to sampling.

Sampling times (h)[1]	Bonneville Dam flow ($m^3/s \times 1,000$)	Eggs		Larvae	
		No.	No./1,000 m^3	No.	No./1,000 m^3
1843–1943	7.24	4	2.8	9	6.4
1951–2051[2]	7.40	3	2.3	0	0.0
2100–2200	7.00	0	0.0	5	3.3
2206–2306	6.74	108	72.2	7	4.7
2314–0014	6.50	7	4.7	9	6.0
0020–0120	6.51	27	18.2	9	6.1
0128–0228	6.58	34	21.9	3	1.9
0234–0334	6.66	3	2.0	7	4.7
0340–0440	6.72	1	0.7	8	5.3
0445–0545	6.77	32	20.6	1	0.6
0553–0623	6.76	18	22.6	7	8.8

[1] Sunset on 25 May was at 2030 hours; sunrise on 26 May was at 0515 hours.
[2] Questionable sampling effort; net was damaged.

after hatching. River kilometer 45 is located in the upper end of the Columbia River estuary (Fig. 1); however, this section of the estuary is a freshwater environment. Larvae were collected from early May through late July, reflecting a protracted spawning period (Table 2). All white sturgeon larvae in 1988 and 1989, and 71% or more in 1990 and 1991, were collected in plankton nets. In 1988 and 1989, larvae were not collected as far downstream as in 1990 and 1991. Undoubtedly, smaller areas of capture in 1988 and 1989 were due to lack of sampling with the 3.0-m beam trawl in these years. All white sturgeon larvae collected in the upper estuary in 1990 and 1991 were collected in the beam trawl. Larvae were collected at depths ranging from 4 to 29 m. When the larvae were collected in plankton nets, they were most likely being transported by water currents, because the nets were fished from an anchored boat.

Catches of white sturgeon larvae during the 12-hour collection at the index site fluctuated with catches ranging from 0.0 to 8.8 larvae/1,000 m^3 (Table 4).

Young of the year

Annual catches of YOY white sturgeon varied considerably, ranging from 11 in 1988 to 273 in 1990 (Table 5). Annual catches shown in Table 5 are not necessarily indicative of YOY abundance in respective years, because sampling gears and schemes were not the same each year. In 1988 and 1989, the 3.0-m beam trawl was not used, whereas in 1990 and 1991 it was used. The beam trawl was more effective at capturing small YOY white sturgeon than was the 7.9-m semiballoon shrimp trawl. Also, in 1990 and 1991, more sampling was conducted in the lower 120 km of the river than in 1988 and 1989.

On the basis of sampling from 1988 through 1991, it appears that YOY white sturgeon are primarily using the section of river extending from rkm 45 to 166 (Table 5). Relatively few YOY white sturgeon were collected in the 68 km of river between Bonneville Dam (rkm 234) and rkm 166; small catches were made at rkm 211 in July 1990 and September 1991.

In 1990 and 1991, YOY white sturgeon were first captured in late June, less than two months after spawning was estimated to have begun. In all four years, YOY white sturgeon appeared to grow well during their first summer; however, monthly mean lengths and weights varied among years (Table 5). During all years, YOY white sturgeon reached a minimum mean total length of 176 mm and a minimum mean weight of 30 g by the end of September. No statistical comparisons among years were done because of small sample sizes, the protracted spawning period of white sturgeon, and the fact that YOY white sturgeon were collected throughout the month.

The YOY white sturgeon were more abundant in deeper areas of the lower Columbia River, at least during daylight; mean minimum depths during trawling efforts in which YOY were captured were ≥12.5 m in all years. Mean maximum depths at which YOY white sturgeon were captured were ≥ 15.8 m in all years. Bottom substrate over which YOY white

Table 5

Summary of young-of-the-year white sturgeon, *Acipenser transmontanus,* catches in the Columbia River downstream from Bonneville Dam, 1988–91. SD = standard deviation.

			Total length (mm)		Weight (g)	
Month	Capture location (rkm)	Number	Mean	SD	Mean	SD
1988						
Jul	126	1	86.0	0.0	3.0	0.0
Aug	127–153	2	134.0	41.0	13.0	9.9
Sep	153	2	235.0	35.4	60.5	29.0
Oct	127–162	6	248.3	9.8	68.2	8.9
Total		11				
1989						
Jul	49–153	17	93.4	25.8	5.0	3.1
Aug	49–153	15	176.7	29.9	31.6	13.5
Sep	46–153	12	224.4	30.4	59.7	18.7
Oct	49–162	56	269.4	23.5	87.4	18.5
Nov[1]	107–120	11	273.8	17.7	90.4	20.2
Total		111				
1990[2]						
Jun	45–120	7	32.1	4.3	<1.0	<1.0
Jul	45–211	125	75.6	27.3	3.2	2.8
Aug	50–166	79	123.8	37.5	12.3	10.4
Sep	49–166	14	222.6	28.4	54.4	19.8
Oct	46–166	48	224.4	28.5	51.9	17.4
Total		273				
1991[3]						
Jun	45–166	27	30.4	4.1	<1.0	<1.0
Jul	45–166	89	55.7	17.8	1.3	1.2
Aug	49–127	55	97.1	27.6	6.1	4.8
Sep	45–211	47	176.4	38.3	29.8	16.2
Total		218				

[1] Sampling for November was conducted on 1 November 1989.
[2] Includes samples collected at rkm 75 from 31 July to 1 August 1990.
[3] No sampling was done in October 1991.

sturgeon were found was predominantly sand; however, much of the bottom in the lower Columbia River is composed of sand. In addition, the bottom trawls could not be used in rocky areas.

During the 20-hour sampling survey from 31 July to 1 August 1990 (sampled from 1155 through 0800 hours) at rkm 75, 52 YOY white sturgeon were collected (Table 6). Over 78% of YOY white sturgeon were collected during hours of darkness, indicating that they were more vulnerable to the trawl at night or that they moved into the sampling area at night. The YOY were collected at depths that ranged from 11 to 15 m.

Discussion

White sturgeon successfully spawned in the lower Columbia River in all years of the study. All white sturgeon eggs collected downstream from Bonneville Dam were probably released by sturgeon spawning in this area and not by sturgeon spawning in the impoundment created by Bonneville Dam. Although white sturgeon spawn in the impoundment upstream from Bonneville Dam (Miller et al.[4]), it is unlikely that any of these eggs are carried through Bonneville Dam. In 1990, Miller et al.[4] collected white sturgeon eggs between rkm 298 and 308. The locations of white sturgeon egg collections upstream from Bonneville

[4] Miller, A. I., P. J. Anders, M. J. Parsley, C. R. Sprague, J. J. Warren, and L. G. Beckman. 1991. Report C. *In* A. A. Nigro (ed.), Status and habitat requirements of the white sturgeon populations in the Columbia River downstream from McNary Dam, p. 82–144. Ann. Rep. to Bonneville Power Admin. (Project 86-50) by Oreg. Dep. Fish Wildl., Wash. Dep. Fish., Natl. Mar. Fish. Serv., and U.S. Fish Wildl. Serv. Avail. Bonneville Power Admin., P.O. Box 3621, Portland, OR 97208.

Dam strongly suggest that eggs are found only in the upper Bonneville Pool, since rkm 298 is about 64 km upstream from the dam.

Spawning in the lower Columbia River in 1988–91 occurred during temperature regimes for successful egg incubation. Successful egg incubation for white sturgeon occurs at temperatures between 10 and 18°C; highest survival and uniform hatching occur between 14 and 16°C (Wang et al., 1985). In our study, we estimated that peak spawning occurred at water temperatures of 12 to 14°C. We estimated that some spawning occurred at water temperatures of 18 or 19°C. Survival for these eggs was probably less than for eggs spawned at lower water temperatures. Wang et al. (1985) observed that substantial white sturgeon embryo mortalities may occur at water temperatures of 18 to 20°C and that temperatures greater than 20°C are clearly lethal. In the Sacramento River, Kohlhorst (1976) observed that water temperatures during the white and green sturgeon spawning period ranged from 7.8 to 17.8°C and that peak spawning occurred at about 14.4°C. It should be noted that Kohlhorst's estimates of the spawning period are based on back calculations of larval ages, rather than on sturgeon eggs. Spawning dates can be more accurately estimated by using eggs rather than larvae.

Sampling for white sturgeon larvae was done with gear that sampled along or very near the bottom; therefore, no data were collected regarding vertical distribution of white sturgeon larvae. However, Stevens and Miller (1970) reported that white or green sturgeon larvae, or both, are primarily demersal in the Sacramento-San Joaquin River System. They caught 33 larvae in 16 bottom sampling efforts and only one larva in eight surface and midwater efforts.

River currents disperse white sturgeon larvae out of spawning and egg incubation areas. Stevens and Miller (1970) noted a direct relationship between river flow and catches of white or green sturgeon larvae, or both, in the Sacramento-San Joaquin Delta. In a laboratory experiment, Brannon et al.[5] observed that white sturgeon larvae swam up the water column after hatching. In addition, Brannon et al.[5] found that the behavior of white sturgeon larvae was affected by current velocity in laboratory experiments. There was an inverse relationship between water velocity and the amount of time larvae spent in the water column.

Dispersal of white sturgeon larvae over a wide area is probably very important in maintaining a stable population of white sturgeon in the lower Columbia River. Wide dispersal allows utilization of more feeding areas and rearing habitats by larval and postlarval white sturgeon and minimizes competition for these limited resources. However, it is also important that white sturgeon not be carried into saline portions of the Columbia River estuary. Brannon et al.[5] found that salinities ≥16 ppt killed white sturgeon larvae and fry.

Food resources for YOY white sturgeon in many of the deeper areas (>12 m) of the lower Columbia River are probably not abundant. Little is known about the diet of YOY white sturgeon in the lower Columbia River; however, limited observations suggest that the amphipod *Corophium salmonis* is the primary prey (Muir et al., 1988). Densities of *C. salmonis* in many of the deeper areas probably are low because of unstable substrates. *Corophium salmonis* is a tubebuilder and requires a more stable substrate to densely populate an area. In 1990, densities of *C. salmonis* at a deep area (19–21 m) at rkm 153 aver-

[5] Brannon, E., S. Brewer, A. Setter, M. Miller, F. Utter, and W. Hershberger. 1985. Columbia River white sturgeon (*Acipenser transmontanus*) early life history and genetics study. Final Rep. to Bonneville Power Admin. (Project 83–316) by Univ. Wash. and Natl. Mar. Fish. Serv., Seattle, 68 p. Avail. Bonneville Power Admin., P.O. Box 3621, Portland, OR 97208.

Table 6

Summary of young-of-the-year white sturgeon, *Acipenser transmontanus,* catches during a 20-hour study at rkm 75 in the lower Columbia River, 31 July–1 August 1990. Sampling was done from 1155 hours on 31 July to 0800 hours on 1 August with a 7.9-m semiballoon shrimp trawl.

Hour[1]	Depth range	No.	No./ha	Length range (mm)	Hour[1]	Depth range	No.	No./ha	Length range (mm)
1155	13–14 m	0	0	—	2130	12–14 m	12	39	57–120
1357	13–14 m	0	0	—	2230	13–15 m	12	38	54–122
1533	10–15 m	0	0	—	0030	12–14 m	15	55	61–141
1702	13–14 m	1	4	79	0218	12–14 m	2	10	82–86
1830	12–14 m	1	4	108	0527	13 m	0	0	—
1933	11–14 m	6	21	79–114	0646	12–13 m	2	10	86–113
2029	12–14 m	1	4	79	0800	12–13 m	0	0	—

[1] Sunset on 31 July was at 2047 hours; sunrise on 1 August was at 0555 hours.

aged less than 105 organisms/m^2 in June through September (McCabe and Hinton[6]). However, in a deep area at rkm 120 that had large numbers of YOY white sturgeon, the density of *C. salmonis* was relatively high in August 1990 (2,289/m^2) but dropped to 433 organisms/m^2 in September (McCabe and Hinton[6]). More research is needed to assess the abundance of benthic organisms in rearing areas of YOY white sturgeon.

Although prey abundance may be low in many of the deeper areas of the lower Columbia River, the substrate in these areas is probably ideal for efficient feeding by YOY white sturgeon. The white sturgeon has a protrusible mouth that is used to suck prey from the bottom. In a laboratory experiment with juvenile Russian sturgeon, *Acipenser gueldenstaedti*, Sbikin and Bibikov (1988) observed that juveniles (≤130 mm) preferred even, sandy bottoms to bottoms with stones or depressions. Juveniles avoided vegetated areas.

Apparently YOY white sturgeon are very effective and efficient predators on prey found in the rearing areas, as evidenced by their rapid growth during the summer and early fall. The YOY white sturgeon reached a mean total length of at least 176 mm by the end of September. Rapid growth during the first growing season reduces natural mortality; by the end of summer or fall, YOY white sturgeon in the lower Columbia River probably have few natural predators.

Sampling equipment used to collect YOY white sturgeon in the lower Columbia River was limited to two types of bottom trawls that could not be used in shallow littoral areas. Observations made during other studies suggest that YOY white sturgeon do not use shallow littoral areas. No YOY white sturgeon have been collected in intensive beach seining efforts at rkm 75 during the last 15 years.[7] Most sampling was done during daylight; limited sampling was done at night. The beach seining location was adjacent to the sampling site where 52 YOY white sturgeon were collected during a 20-hour study in 1990. No YOY white sturgeon were collected in backwaters and shoreline areas during limited beach seining tows in the lower Columbia River in August 1988 (McCabe et al.[8]).

We conclude that white sturgeon spawned successfully in the lower Columbia River during the period 1988 through 1991. Collection of YOY white sturgeon indicated that recruitment occurred in all years.

[6] McCabe, G. T., Jr., and S. A. Hinton. 1991. Report D. *In* A. A. Nigro (ed.), Status and habitat requirements of white sturgeon populations in the Columbia River downstream from McNary Dam, p. 145–180. Ann. Rep. to Bonneville Power Admin. (Project 86–50) by Oreg. Dep. Fish Wildl., Wash. Dep. Fish., Natl. Mar. Fish. Serv., and U.S. Fish Wildl. Serv. Avail. Bonneville Power Admin., P.O. Box 3621, Portland, OR 97208.

[7] Richard D. Ledgerwood, National Marine Fisheries Service, P.O. Box 155, Hammond, Oregon 97121. Personal commun., 1992.

[8] McCabe, G. T., Jr., S. A. Hinton, and R. J. McConnell. 1989. Report D. *In* A. A. Nigro (ed.), Status and habitat requirements of white sturgeon populations in the Columbia River downstream from McNary Dam, p. 167–207. Ann. Rep. to Bonneville Power Admin. (Project 86–50) by Oreg. Dep. Fish Wildl., Wash. Dep. Fish., Natl. Mar. Fish. Serv., and U.S. Fish Wildl. Serv. Avail. Bonneville Power Admin., P.O. Box 3621, Portland, OR 97208.

Acknowledgments

We thank personnel from the National Marine Fisheries Service, Hammond, Oregon, and the Washington Department of Fish and Wildlife, Battle Ground, Washington, who assisted in field sampling or sample analyses. Also, we thank Benjamin Sandford for assistance with the statistical analysis and two anonymous reviewers for their constructive comments. The study was funded primarily by the Bonneville Power Administration.

Literature cited

Beer, K. E.
1981. Embryonic and larval development of white sturgeon (*Acipenser transmontanus*). M.S. thesis, Univ. Calif., Davis, 93 p.

Buchanan, T. J., and W. P. Somers.
1969. Discharge measurements at gaging stations, Chapter A8, 65 p. Techniques of water-resources investigations of the United States Geological Survey, Book 3, Applications of hydraulics. U.S. Gov. Printing Office, Washington, D.C.

Cochnauer, T. G., J. R. Lukens, and F. E. Partridge.
1985. Status of white sturgeon, *Acipenser transmontanus*, in Idaho. *In* F. P. Binkowski and S. I. Doroshov (eds.), North American sturgeons: biology and aquaculture potential, p. 127–133. Dr. W. Junk, Dordrecht, Netherlands.

Craig, J. A., and R. L. Hacker.
1940. The history and development of the fisheries of the Columbia River. U.S. Dep. Interior, Bur. Fish., Bull. 32(49):133–216.

Kohlhorst, D. W.
1976. Sturgeon spawning in the Sacramento River in 1973, as determined by distribution of larvae. Calif. Fish Game 62:32–40.

McCabe, G. T., Jr., and L. G. Beckman.
1990. Use of an artificial substrate to collect white sturgeon eggs. Calif. Fish Game 76:248–250.

Muir, W. D., R. L. Emmett, and R. J. McConnell.
1988. Diet of juvenile and subadult white sturgeon in the lower Columbia River and its estuary. Calif. Fish Game 74:49–54.

Parsley, M. J., L. G. Beckman, and G. T. McCabe Jr.
1993. Spawning and rearing habitat use by white sturgeons in the Columbia River downstream from McNary Dam. Trans. Am. Fish. Soc. 122:217–227.

Ryan, B. F., B. L. Joiner, and T. A. Ryan Jr.
1985. Minitab handbook. PWS-KENT Pub. Co., Boston, MA, 386 p.

Sbikin, Yu. N., and N. I. Bibikov.
1988. The reaction of juvenile sturgeons to elements of bottom topography. J. Ichthyol. 28:155–160.

Scott, W. B., and E. J. Crossman.
1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. 184, 966 p.

Stevens, D. E., and L. W. Miller.
1970. Distribution of sturgeon larvae in the Sacramento-San Joaquin River system. Calif. Fish Game 56:80–86.

Wang, Y. L., F. P. Binkowski, and S. I. Doroshov.
1985. Effect of temperature on early development of white and lake sturgeon, *Acipenser transmontanus* and *A. fulvescens*. Environ. Biol. Fishes 14:43–50.