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White Sturgeon Spawning and Rearing Habitat in the Lower Columbia River

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Abstract.—Estimates of spawning habitat for white sturgeons *Acipenser transmontanus* in the tailraces of the four dams on the lower 470 km of the Columbia River were obtained by using the Physical Habitat Simulation System of the U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology to identify areas with suitable water depths, water velocities, and substrates. Rearing habitat throughout the lower Columbia River was assessed by using a geographic information system to identify areas with suitable water depths and substrates. The lowering of spring and summer river discharges from hydropower system operation reduces the availability of spawning habitat for white sturgeons. The four dam tailraces in the study area differ in the amount and quality of spawning habitat available at various discharges; the differences are due to channel morphology. The three impoundments and the free-flowing Columbia River downstream from Bonneville Dam provide extensive areas that are physically suitable for rearing young-of-the-year and juvenile white sturgeons.

The productivity of lotic environments is controlled by four factors: flow regime (river hydrograph), physical habitat structure (channel morphology and substrate), water quality (including temperature), and energy inputs from the watershed (nutrients and organic matter) (Karr and Dudley 1978). The interaction of these factors determines primary and secondary production, which ultimately affect the status of fish populations. Restriction or limitation of any one of these factors during any life stage sets the adult population size (Orth 1987). If a riverine environment and thus the interaction of these factors is altered, changes to fish populations and how they respond to management strategies can be expected.

Development of the Columbia River basin for hydroelectric power generation during the mid-1900s profoundly altered the riverine environment. Construction and operation of dams in the Columbia River basin altered the flow regime and increased water depths, which resulted in reduced water velocities over extensive areas. These changes have affected the fisheries within the basin.

An understanding of the potential of the altered riverine environment to support all life stages of white sturgeon *Acipenser transmontanus* is necessary for fishery managers. White sturgeons are susceptible to overharvest, and the recent changes to their physical environment may make them more so. Dams on other river systems have adversely affected sturgeon populations (Khoroshko 1972; Votinov and Kas'yanov 1978; Deacon et al. 1979; Rochard et al. 1990).

Prior to development of the Columbia Basin, the white sturgeons were subjected to an intense commercial fishery that peaked at nearly 2,500,000 kg in 1892 and fell to less than 45,400 kg in 1899 (Craig and Hacker 1940). The adoption of management regulations allowed the stocks to recover somewhat, but yields did not increase substantially until the 1970s (Rieman and Beamesderfer 1990). The environmental changes associated with the cultural development of the basin has led to a collection of white sturgeon stocks bounded by dams and may preclude natural recovery to historical levels.

Recent research has documented spawning and identified the habitat used by various life stages of white sturgeons in the lower Columbia River (Parsley et al. 1993). Successive year-class failures and poor recruitment to young of the year have been noted in the three impoundments downstream from McNary Dam, yet spawning and recruitment in the unimpounded river downstream from Bonneville Dam occurred during the same years (National Biological Survey, National Marine Fisheries Service, unpublished data). In this paper we estimate the amount of habitat available for spawning and rearing (young-of-the-year and juvenile) white sturgeons in the three impoundments and free-flowing river that constitute the lower 470 km of the Columbia River. In doing this, we also provide habitat suitability criteria curves for spawning, young-of-the-year, and juvenile white sturgeons that may be used by other investigators.

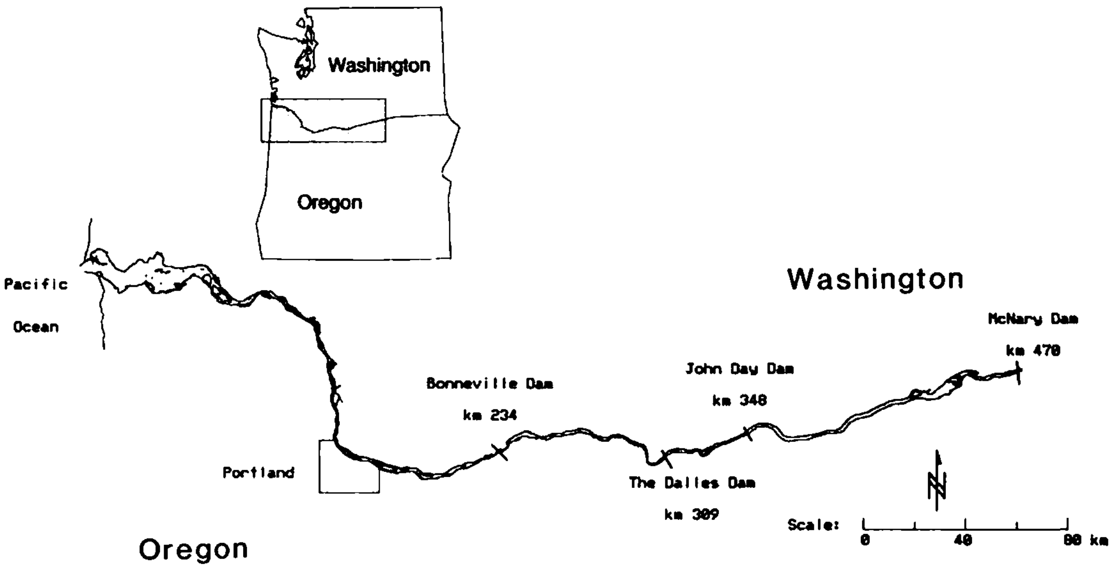

FIGURE 1.—The Columbia River downstream from McNary Dam, with locations of the four mainstem dams. River flow is from right to left.

Study Area

This study was conducted in the Columbia River from the mouth (river kilometer 0) to McNary Dam (river km 470). The four dams within the study area are operated primarily for hydroelectric power generation and divide the river into three impoundments, Bonneville Pool, The Dalles Pool, and John Day Pool, and a free-flowing river reach (Figure 1). Bonneville Dam was closed in 1938, The Dalles Dam in 1957, John Day Dam in 1967, and McNary Dam was closed in 1953. The four river reaches differ in length, surface area, and other physical characteristics (Table 1). Ebel et al. (1989) and Anonymous (1991) provided a background on the biotic and abiotic environment and the alterations to the environment caused by development and operation of the numerous hydroelectric and water diversion dams in the Columbia River basin.

River discharges through the study area are regulated by storage reservoirs located upriver in the Columbia and Snake river basins. The result has been higher river discharges during winter and lower discharges during spring and summer, relative to the historic hydrograph (Ebel et al. 1989). The reservoirs in the study area have little storage capacity, and discharges through the dams are run-of-the-river. Therefore, mean daily discharge at each dam is similar, though hourly hydrographs of discharge among dams can be variable. Typically, hourly discharge at Bonneville Dam is relatively stable, whereas discharges at McNary, John Day, and The Dalles dams peak in the morning and are lower at night.

Two types of spill may occur at each dam during spring and summer: forced spill, when discharge is greater than the hydraulic capacity of the turbines (Table 1), and planned spill, to aid in passing outmigrating juvenile salmonids. Usually, planned spill is during the evening, when total discharge is lowest.

Water elevations within each river reach are affected by river discharge, pondage in the three impoundments, and tides in the lower river reach. Pondage is regulated by the rule curves in effect at each dam. Water elevations fluctuate more in the dam tailraces than in the forebays. The greatest fluctuations occur in the Bonneville Dam tailrace and in the John Day Dam forebay (Table 1).

Methods

Two methodologies were used to quantify the physical habitat for spawning and rearing white sturgeon. We used the Physical Habitat Simulation System (PHABSIM; Bovee 1982) to evaluate habitat available for spawning white sturgeons by determining the relation between river discharge and spawning habitat downstream from each dam within the study area, and we used a geographic information system (GIS) to identify and quantify habitat for rearing (young-of-the-year and juvenile) white sturgeon throughout the study area.

TABLE 1.—Characteristics of the four river reaches in the lower 470 km of the Columbia River. Surface, bathymetry, and substrate areas were derived during this study.

Characteristic	Lower river	Bonneville Pool	The Dalles Pool	John Day Pool
Length (km)	234	75	39	122
Surface area (ha)	61,148	7,632	3,639	19,781
Range in water surface elevations[a] (m)				
Upper end	2.6–8.6	22.3–25.9	48.3–50.4	80.5–82.4
Lower end	Sea level	21.5–23.2	47.5–48.6	77.2–81.6
Hydraulic capacity of the upstream dam (m³/s)	8,550	10,645	10,022	13,533
Area (ha) between bathymetric contours[b] (m):				
0–1.82 (0–1.52)	25,172	1,036	195	2,500
1.83–3.66 (1.53–4.57)	8,289	499	139	2,504
3.67–5.49 (4.58–7.62)	6,787	1,010	336	2,228
5.50–9.14 (7.63–10.67)	8,076	1,748	896	1,936
9.15–18.29 (10.68–13.72)	12,024	2,993	1,485	1,589
>18.29 (13.73–19.81)	710	346	587	2,982
(>19.81)				6,043
Substrate areas (ha)				
Hard clay	4	0	0	0
Mud–silt	0	0	286	7,793
Sand	60,397	6,729	573	6,793
Gravel	142	357	175	3,645
Cobble	236	195	1,743	1,399
Boulder	369	103	198	69
Bedrock	0	248	663	83

[a] From mean daily minimums and maximums recorded at each dam during 1986 and 1988.

[b] Depth contour figures are from nautical charts of the lower river, Bonneville, and The Dalles pools; parenthetical numbers are depth contours of John Day Pool, taken from nautical charts that used a different depth contour scale.

Both methods determine the overall quality as habitat of a particular unit of area of the river. Summing those areas gives an estimate of the quantity of habitat for each river reach. Temporal estimates of habitat were made with the PHABSIM, but not with the GIS. The size of the study area precluded our using PHABSIM throughout the length.

Criteria that defined habitat quality for spawning and rearing were developed as standards for comparisons among the areas. Parsley et al. (1993) described the habitat used by various life stages of white sturgeon within the study area. We used the data from their paper to construct microhabitat criteria curves that depict the suitability of depths, mean water column velocities, and substrates for white sturgeon spawning, young of the year (20–320 mm total length), and juveniles (150–1,030 mm fork length), and the suitability of water temperatures for white sturgeon spawning. The criteria curves (Figures 2, 3) define the suitability of each habitat descriptor on a scale of 0 to 1 (0 = unsuitable and 1 = most suitable). The curves were fit by eye to the habitat use data presented in Parsley et al. (1993) and presented again here (Figures 2, 3). The resulting curves were critiqued by other white sturgeon researchers. Microhabitat criteria curves are often developed in this manner (Bovee and Zuboy 1988).

Spawning habitat.—The relation between river discharge and white sturgeon spawning habitat downstream from each dam was assessed through the computer models of the PHABSIM. PHABSIM has been described extensively (Stalnaker 1979; Bovee 1982; Milhous et al. 1989), and the following discussion is drawn largely from Bovee (1986). Measurements of water depth, velocities, and substrates along transects placed in the study area divide the river into a large number of rectangular cells (plane view). Each cell has a unique combination of depth, velocity, and substrate. Depth and velocities will vary with discharge, while substrate is fixed. Cells on the edge of the river will vary in surface area as water elevations rise and fall, while those always inundated have a fixed surface area. Changes in depth and velocity at points along each transect at unmeasured discharges are predicted by hydraulic simulation models described by Bovee and Milhous (1978) and Milhous et al. (1989). Habitat is estimated when the predicted water depth, velocity, and substrate for each cell is evaluated against the microhabitat criteria used to define habitat. The depth, velocity, and substrate for each cell are compared

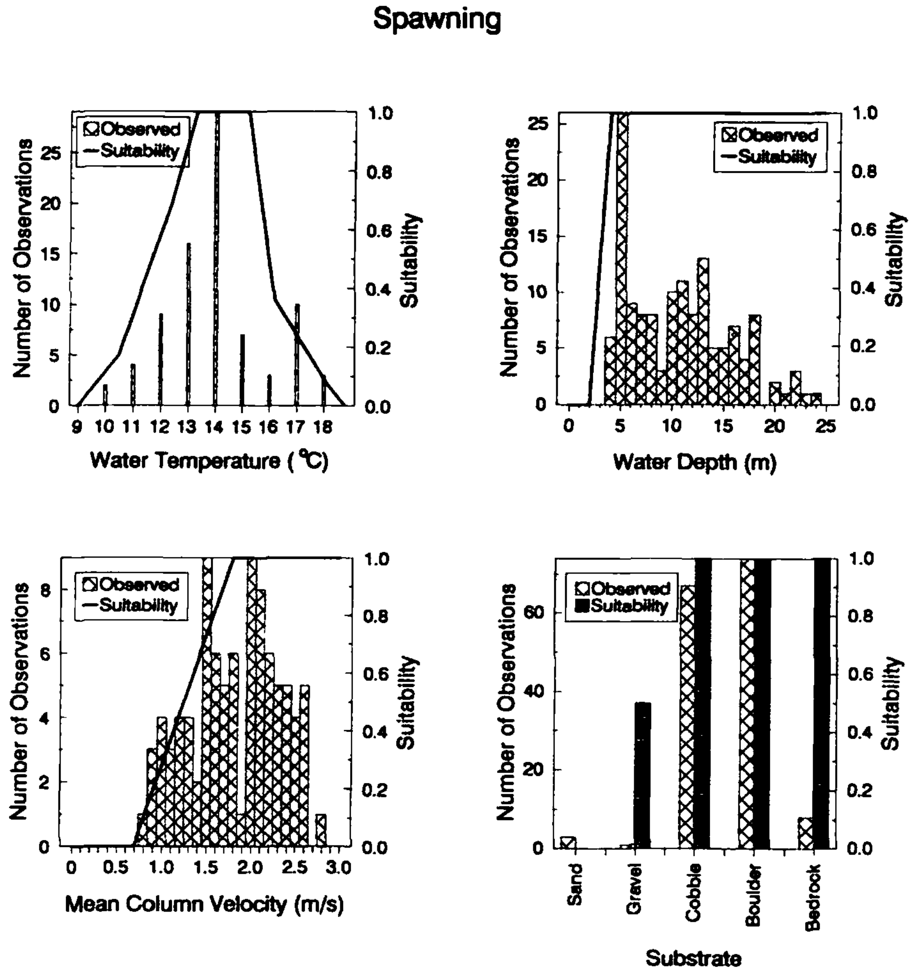

FIGURE 2.—Microhabitat criteria curves depicting the suitability of water temperatures, depths, mean column velocities, and substrates for spawning white sturgeons. Hatched bars are the data from which the curves were drawn (Parsley et al. 1993).

with the criteria to determine an overall habitat quality for each cell. This value is then multiplied by the surface area of the cell to obtain an index of microhabitat, called weighted usable area (WUA). Summing the WUA for all cells gives the WUA for the study site for a given discharge.

We simulated spawning habitat at discharges representative of those that have occurred after development of the Columbia River basin. We simulated spawning habitat for discharges ranging from 1,415.6 to 14,156 m^3/s at 707.8 m^3/s intervals. Mean daily river discharge at McNary Dam from 1952 through 1992 has ranged from 1,118 to 22,593 m^3/s, and monthly averages during this period ranged from 2,124 to 17,664 m^3/s (Figure 4).

Parsley et al. (1993) determined that spawning by white sturgeons occurred within 8 km of the four dams within the study area. Therefore, we restricted our estimates of spawning habitat to these areas. The areas investigated constituted about 3% of the length of the lower river, and about 11, 21, and 7% of the lengths of the Bonneville, The Dalles, and the John Day pools. Transects were surveyed in each tailrace to obtain river cross-section profiles, detailing riverbed elevations, mean water-column velocities, and substrates at verticals along each transect for input into the hydraulic simulation program IFG4 of the PHABSIM (Milhous et al. 1989). Five transects were surveyed downstream from Bonneville Dam, eight downstream from The Dalles Dam, five downstream from John

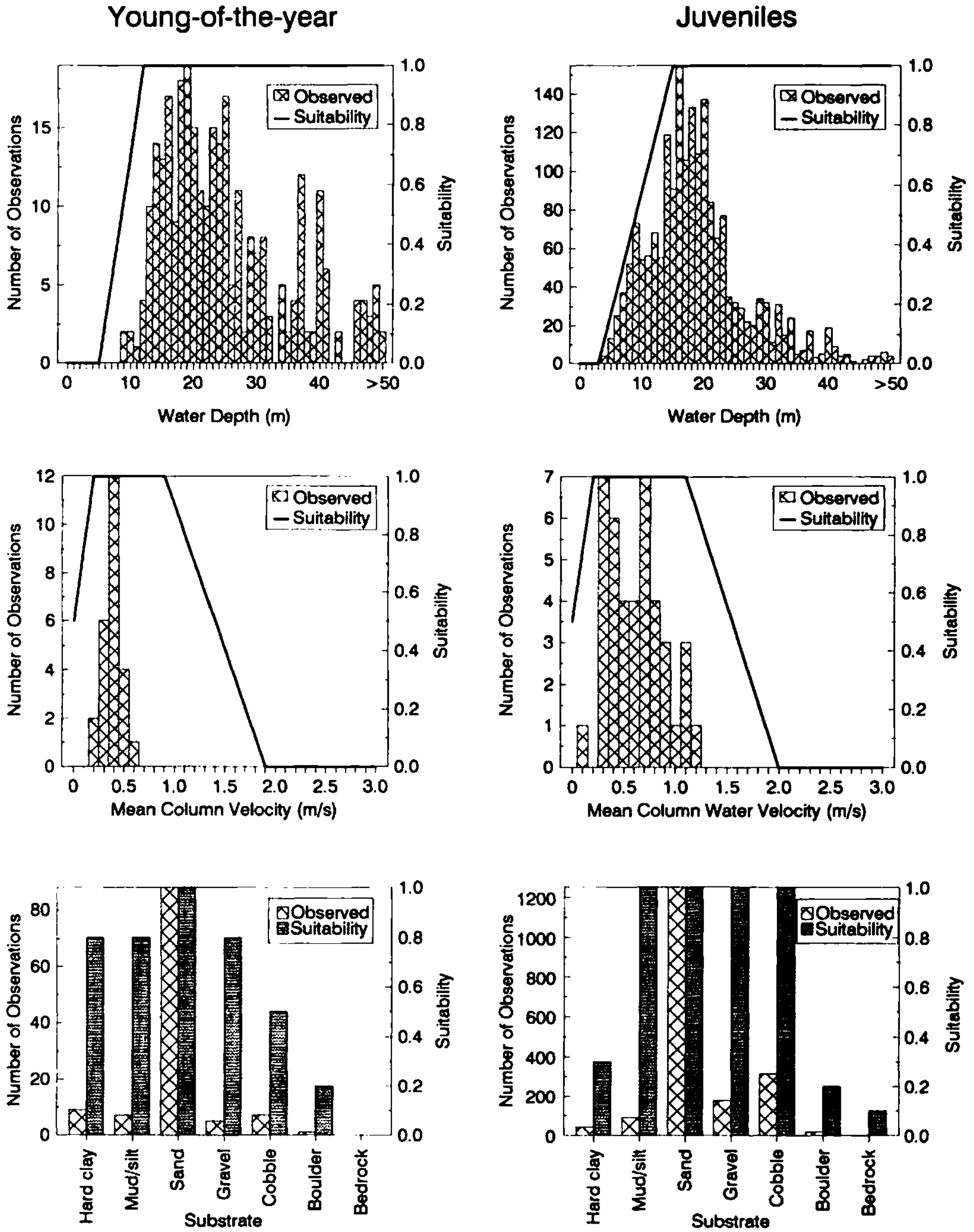

FIGURE 3.—Microhabitat criteria curves depicting the suitability of water depths, mean column velocities, and substrates for young-of-the-year and juvenile white sturgeons. Hatched bars are the data from which the curves were drawn (Parsley et al. 1993).

Day Dam, and seven downstream from McNary Dam (Figure 5). Distances (nearest 0.3 m) between individual transects were measured with an electronic distance meter (EDM), and elevations (height above mean sea level, nearest 0.3 cm) were determined through standard surveying techniques. We used the EDM to measure the distance to a boat positioned along each transect to describe

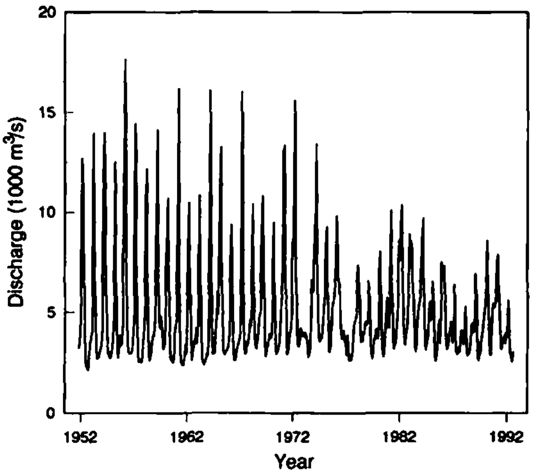

FIGURE 4.—Mean monthly river discharges at McNary Dam on the lower Columbia River, 1952–1993.

bed elevations and to obtain water velocities for model calibration. Water surface elevations (nearest 0.3 cm) were measured at each transect at several discharges. Information about individual transects is reported in the Appendix.

We used least-squares regression to determine the relation between tailwater elevation at the dam and water elevation at each transect. Each dam is an upstream hydraulic control, and hourly records of tailwater elevation and river discharge are kept by the U.S. Army Corps of Engineers. Regressions were based on hourly data for the months of April–July from one or more years. This relation predicted the tailwater elevation at each dam for the discharges to be simulated. These predicted tailwater elevations were then used to predict the water surface elevation at each transect for each discharge to be simulated.

The relation between discharge and white sturgeon spawning habitat within the area described by the transects was established with the HABTAE program of the PHABSIM (Milhous et al. 1989). This program integrated the output from the hydraulic simulation model (predicted depths, water velocities, and substrates at selected discharges) with the microhabitat criteria curves that defined habitat used by spawning white sturgeon. The lowest suitability for depth, mean column velocity, and substrate present for each cell (lowest limiting parameter approach, Bovee 1982) was used as the composite suitability index (CS) of spawning habitat for each cell. We multiplied model output by

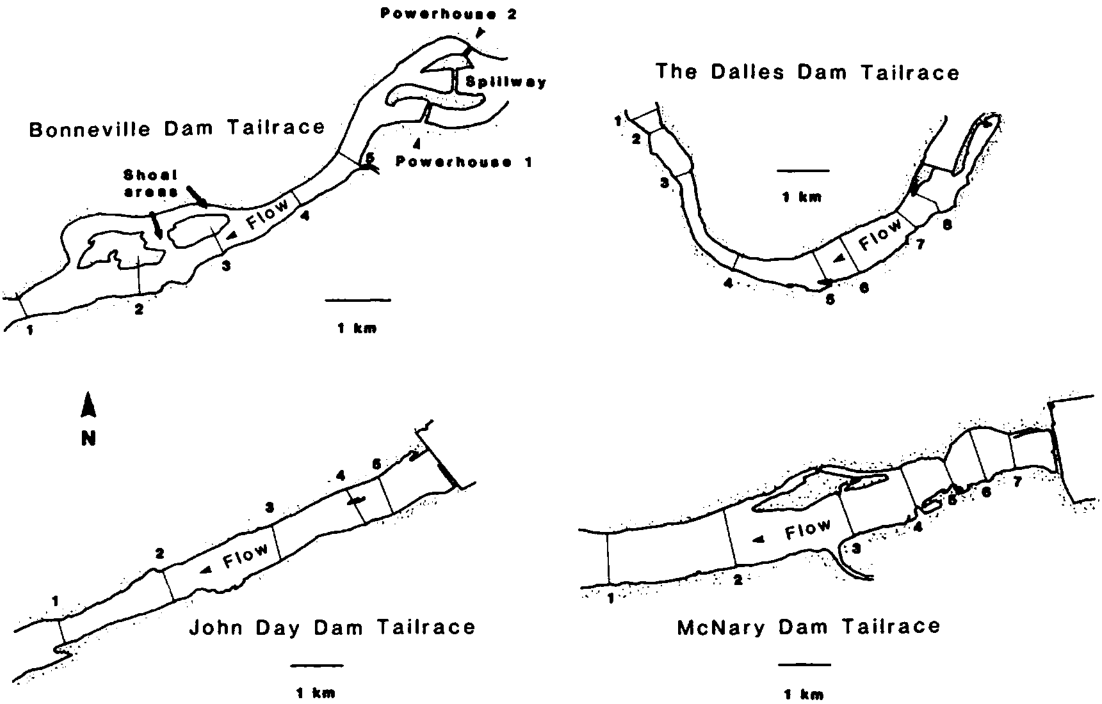

FIGURE 5.—Locations of transects placed for hydraulic and spawning habitat simulations in the tailraces of Bonneville, The Dalles, John Day, and McNary dams.

TABLE 2.—Microhabitat criteria values for young-of-the-year and juvenile white sturgeon assigned to each depth contour depicted on nautical charts of the study area. Values were obtained by averaging criteria values at 0.3-m intervals within each contour.

Depth contour (m)	Average criteria value	
	Young of the year	Juvenile
Lower river reach, Bonneville Pool, and The Dalles Pool		
0–1.82	0.00	0.00
1.83–3.66	0.00	0.01
3.67–5.49	0.02	0.14
5.50–9.14	0.37	0.37
9.15–18.29	0.95	0.85
>18.29	1.00	1.00
John Day Pool		
0–1.52	0.00	0.00
1.53–4.57	0.00	0.04
4.58–7.62	0.20	0.27
7.63–10.67	0.63	0.52
10.68–13.72	0.97	0.78
13.73–19.81	1.00	0.99
>19.81	1.00	1.00

individual reach lengths to obtain surface areas to allow comparisons of spawning habitat within different reaches.

Daily spawning habitat from 1985 through 1991 was determined by integrating mean daily discharge and water temperature from April through July with the spawning habitat versus discharge relation for each tailrace. Mean daily discharge and water temperature for each dam were obtained from records maintained by the U.S. Geological Survey (Water Resources Division, Portland, Oregon), the U.S. Army Corps of Engineers (North Pacific Division, Portland, Oregon), the Fish Passage Center (Portland, Oregon), and the U.S. Fish and Wildlife Service (Cook, Washington). Daily spawning habitat (WUA) was averaged monthly and annually. Variation in spawning habitat for each tailrace and year was assessed by calculating the coefficient of variation (CV = 100·SD/mean) in monthly habitat during 1985–1991.

Rearing habitat.—The geographic information system (GIS) EPPL7[1] was used to identify areas in each river reach that had suitable water depths and substrates for young-of-the-year and juvenile white sturgeons. A GIS consists of computer hardware and software tools that unite computerized mapping and databases to provide analysis and display of geographically oriented data. Star and Estes (1990) and Meaden and Kapetsky (1991) provided a background and applications of GIS. We did not use the information from the PHABSIM analysis for spawning habitat to also investigate rearing habitat. The areas described by the transects used in the PHABSIM analysis were relatively small (3, 11, 21, and 7% of the lengths of the lower river and the Bonneville, The Dalles, and John Day pools, respectively). Use of the GIS enabled us to identify and quantify rearing habitats throughout the length of the study area, including the areas investigated for spawning habitat.

Habitat for young-of-the-year and juvenile white sturgeons was quantified by using the GIS to identify areas in each river reach as suitable or unsuitable for these life stages. Mean column water velocities for the entire study area were not available; hence, analyses were limited to depth and substrate. The criteria curves for water velocities reveal that young-of-the-year and juvenile white sturgeons will use a wide range of water velocities (Figure 3). Water depth contours were obtained from nautical charts produced by the National Oceanic and Atmospheric Administration (National Ocean Service, Riverdale, Maryland). Substrate contours were hand-drawn from an assimilation of field measurements from this and other studies, preimpoundment aerial photographs, and the nautical charts. Depths were depicted as discrete contours; therefore, we assigned a suitability to each depth contour by averaging, at 0.3-m intervals, suitabilities from the microhabitat criteria (Table 2). Substrate categories were also assigned suitabilities from the microhabitat criteria depicted in Figures 2 and 3.

We did not consider the entire estuary in our estimates of rearing habitat. High salinity in the estuary precludes the use of extensive areas of the unimpounded lower river reach by young-of-the-year and juvenile white sturgeons. The extent of saltwater intrusion is dynamic and depends on river discharge and tides (Fox et al. 1984). Though adult white sturgeons move freely between fresh, brackish, and saline waters, young of the year and smaller juveniles cannot. The ability of white sturgeons to tolerate salinity increases with size (McEnroe and Cech 1985). Therefore, for this analysis we used river kilometer 45 as the downstream boundary for young of the year and river kilometer 30 as the downstream boundary for juveniles.

For young-of-the-year and juvenile white sturgeons, a composite suitability index for each cell

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[1] The mention of commercial trade names does not imply endorsement by the National Biological Survey.

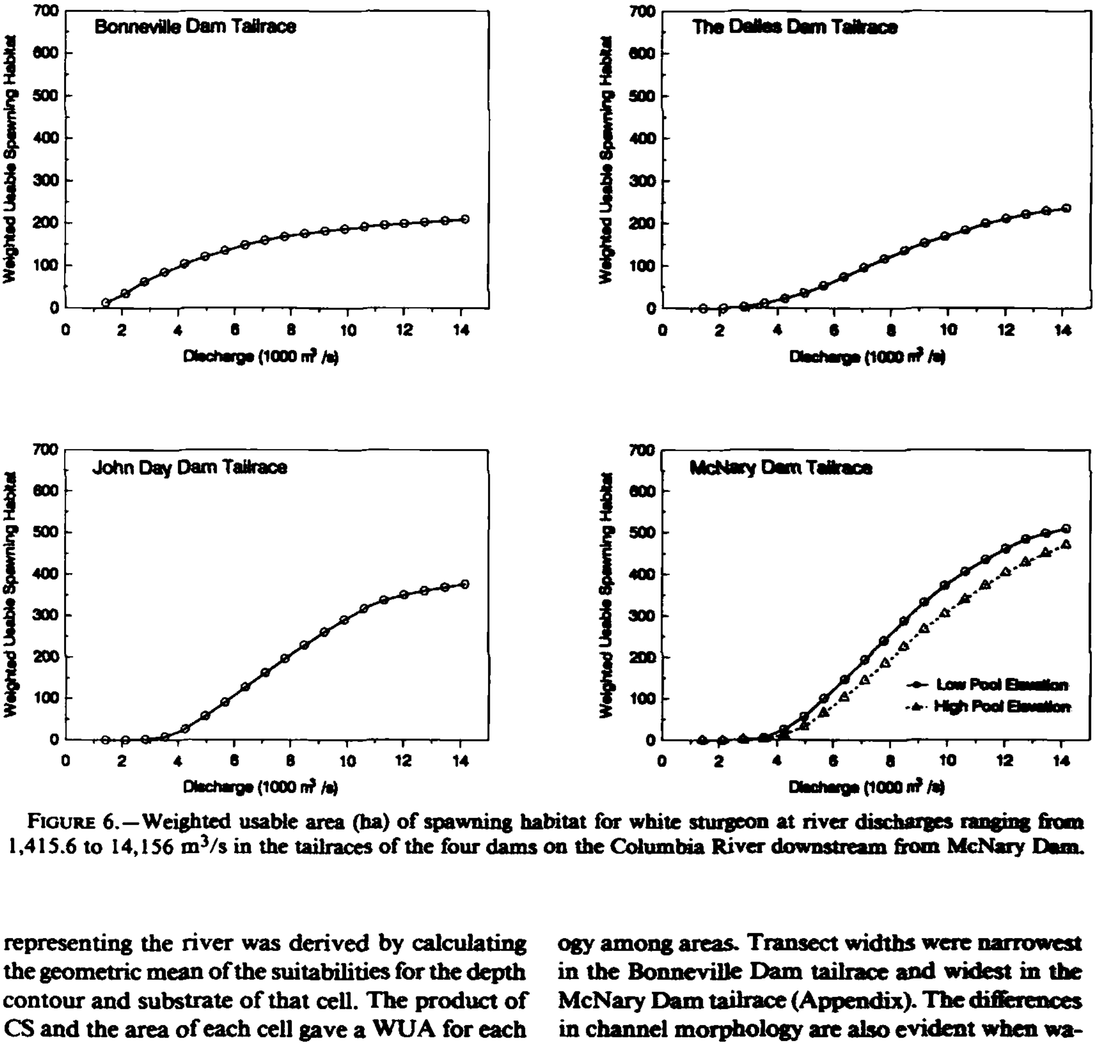

FIGURE 6.—Weighted usable area (ha) of spawning habitat for white sturgeon at river discharges ranging from 1,415.6 to 14,156 m^3/s in the tailraces of the four dams on the Columbia River downstream from McNary Dam.

representing the river was derived by calculating the geometric mean of the suitabilities for the depth contour and substrate of that cell. The product of CS and the area of each cell gave a WUA for each cell. Summing all cells gave a WUA for each river reach, and identified areas within each reach that were usable (CS = 0.001–1.00) or unusable (CS = 0). Quality rankings of low (CS = 0.001–0.40), medium (CS = 0.41–0.80), or high (CS = 0.81–1.00) were assigned to each cell to provide comparisons of the relative quality of the usable habitat among the reaches.

Results

Spawning Habitat

The amount of spawning habitat for white sturgeons increased in each tailrace as discharge increased (Figure 6). The rate of increase and the amount of spawning habitat differed among tailraces because of differences in channel morphology among areas. Transect widths were narrowest in the Bonneville Dam tailrace and widest in the McNary Dam tailrace (Appendix). The differences in channel morphology are also evident when water surface gradients are compared (Figure 7). The Bonneville Dam tailrace has a higher water surface gradient than the other tailraces. Higher gradients will cause faster water velocities. Spawning habitat increased in each tailrace because the gradient, and therefore water velocities, increased with discharge. Each tailrace had extensive areas of suitable water depths and substrates for spawning at all simulated discharges. These areas became higher-quality spawning habitat as the water velocities through them increased. The Bonneville Dam tailrace provides more high-quality spawning habitat for white sturgeon at discharges that are lower than discharges needed to provide even low- to moderate-quality spawning habitat in the other three tailraces.

Weighted usable area, when expressed as the percentage of the total area of each tailrace, is

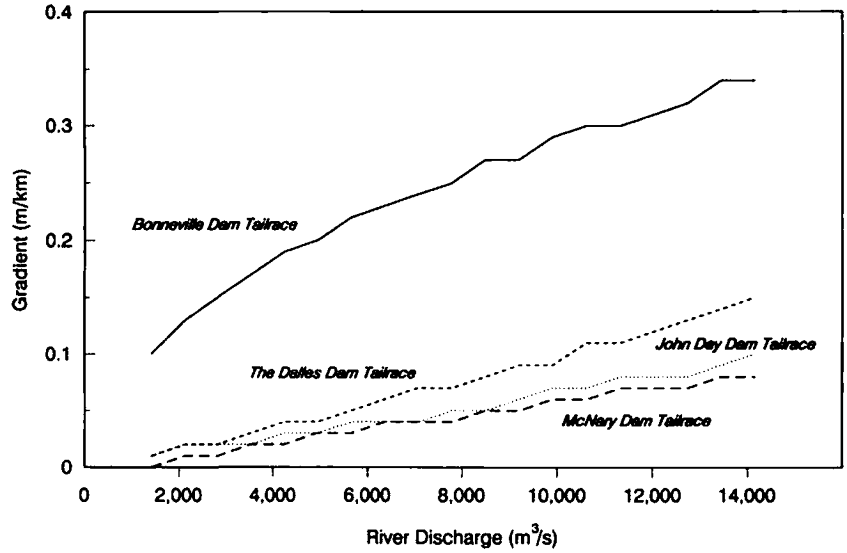

FIGURE 7.—Water surface gradients between the lower and uppermost transects in four dam tailraces on the lower Columbia River at various river discharges.

maximized at 6,370 m^3/s in the Bonneville tailrace, but continues to increase with increasing discharge in the other tailraces, indicating that the quality of the usable habitat present in these tailraces improves with increasing discharge (Figure 8).

Bonneville Dam tailrace.—Habitat suitable for white sturgeon spawning was present at all simulated river discharges in the Bonneville Dam tailrace (Figure 6). The amount of habitat increased as discharge increased, and high-quality habitat was present at discharges greater than 2,120 m^3/s. River discharge during the white sturgeon spawning period is seldom less than 2,120 m^3/s at Bonneville Dam. Model output of white sturgeon spawning habitat in the Bonneville Dam tailrace revealed spawning habitat first appeared along transect 3 (Figure 5) and extended upriver and downriver as discharge increased. Cells with CSs of 0.81 or greater (high-quality habitat) first appeared along this transect at discharges near 2,120 m^3/s.

Hydraulic simulations of water depths and velocities at different discharges in the river channels downstream from the two powerhouses and the spillway basin were not possible because water elevations and discharges in each channel are unrelated. The total river discharge can pass through the channels in any combination, and different discharges may occur at the same water elevation, thus precluding valid simulations. However, each channel is similar in physical morphometry to the main channel described by transects 1–5, and suitable spawning habitat is probably present in each channel during periods of power generation or spill.

The Dalles Dam tailrace.—Spawning habitat was present, although low in quantity and quality, in this tailrace when river discharge was 2,120 m^3/s. Appreciable increases in habitat are not evident until discharges exceed 3,540 m^3/s (Figure 6). Model output of white sturgeon spawning habitat and discharge in The Dalles Dam tailrace showed that usable habitat first appeared along transect 8 (Figure 5) and extended upriver and downriver as discharge increased. Cells with CSs of 0.81 or greater first occurred along transect 8 at discharges near 4,250 m^3/s.

John Day Dam tailrace.—Spawning habitat was present in minimal area and quality in this tailrace when discharge was 2,830 m^3/s (Figure 6). Model output of white sturgeon spawning habitat in the John Day Dam tailrace showed spawning habitat first appeared along transects 4 and 5 (Figure 5) and extended downriver as discharge increased. Cells with CSs of 0.81 or greater first occurred along these transects at discharges near 6,660 m^3/s.

McNary Dam tailrace.—It was necessary to derive two relations describing the amount of white sturgeon spawning habitat in the McNary Dam tailrace. The U.S. Army Corps of Engineers has maintained reservoir elevations in John Day Pool (measured at John Day Dam) at two levels, ap-

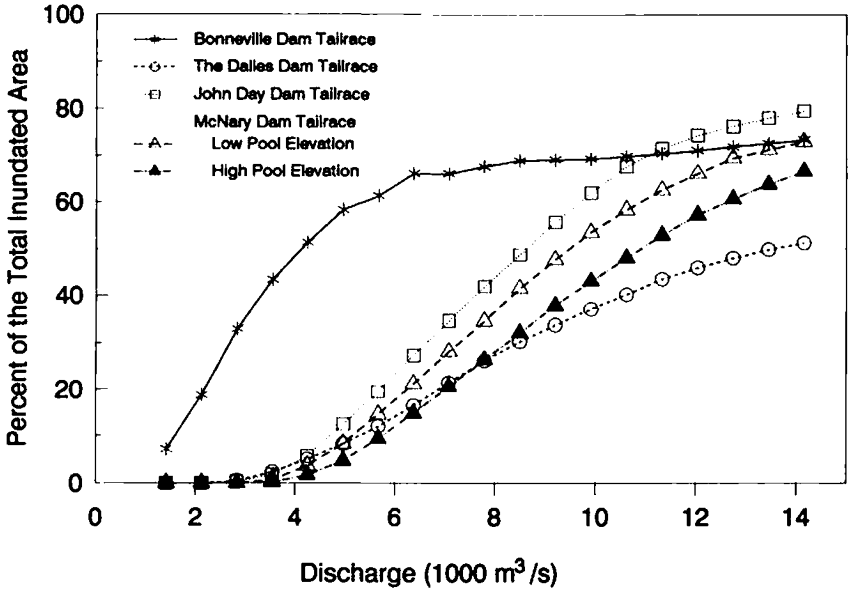

FIGURE 8.—Weighted usable spawning area for white sturgeon at discharges through four lower Columbia River reaches expressed as the percent of the total inundated area of each reach at each discharge.

proximately 80.5 m and 81.4 m above mean sea level. Typically, the pool has been kept at the lower elevation during winter and spring, and the higher elevation was maintained starting in mid to late June through the summer for irrigation withdrawals. During 1988, however, the reservoir elevation was maintained at the higher level throughout the year.

Habitat suitable for spawning was present in this tailrace when river discharge was at least 2,830 m^3/s at either pool elevation (Figure 6). Higher discharges were needed to achieve the same usable area or WUA when the pool elevation was maintained at the 81.4 m elevation than at 80.5 m. Model output of spawning habitat in the McNary Dam tailrace showed spawning habitat along transect 7 (Figure 5) at lower discharges, which extended downriver as discharge increased. Cells with CSs of 0.81 or greater first occurred along this transect at a discharge near 7,080 m^3/s.

Time Series Analysis of Spawning Habitat

The amount of habitat suitable for white sturgeon spawning varied in all areas during 1985–1991 (Figure 9) and was controlled by discharge and water temperature. Tailraces of the John Day and McNary dams had the greatest variation in monthly spawning habitat. The effect of reduced discharge on spawning habitat during low-water years (1985, 1987–1989) is evident in the graphs depicting monthly spawning habitat in the tailraces of The Dalles, John Day, and McNary dams (Figure 9). The reduced discharges in these years had less of an effect on spawning habitat in the Bonneville Dam tailrace because the physical morphology of this tailrace (a narrow channel with a high gradient) created spawning habitat at discharges lower than discharges needed to create spawning habitat in the other tailraces. The role of temperature in defining the spawning period and its effect on total spawning habitat was evident in each year (particularly in 1986) and in all tailraces.

Creation of an annual time series by use of temperature-conditioned annual average spawning habitat revealed that the Bonneville Dam tailrace provided more spawning habitat during the low-water years (1985, 1987–1989) than the other three tailraces (Figure 10). More spawning habitat was present each year in the tailraces of the Bonneville and John Day dams, and in the McNary Dam tailrace in 1988, than in The Dalles Dam tailrace. The coefficient of variation in annual spawning habitat was generally lowest in the Bonneville Dam tailrace (Figure 11), which shows that the amount of spawning habitat did not fluctuate during a given year as much in this tailrace as it did in the other tailraces.

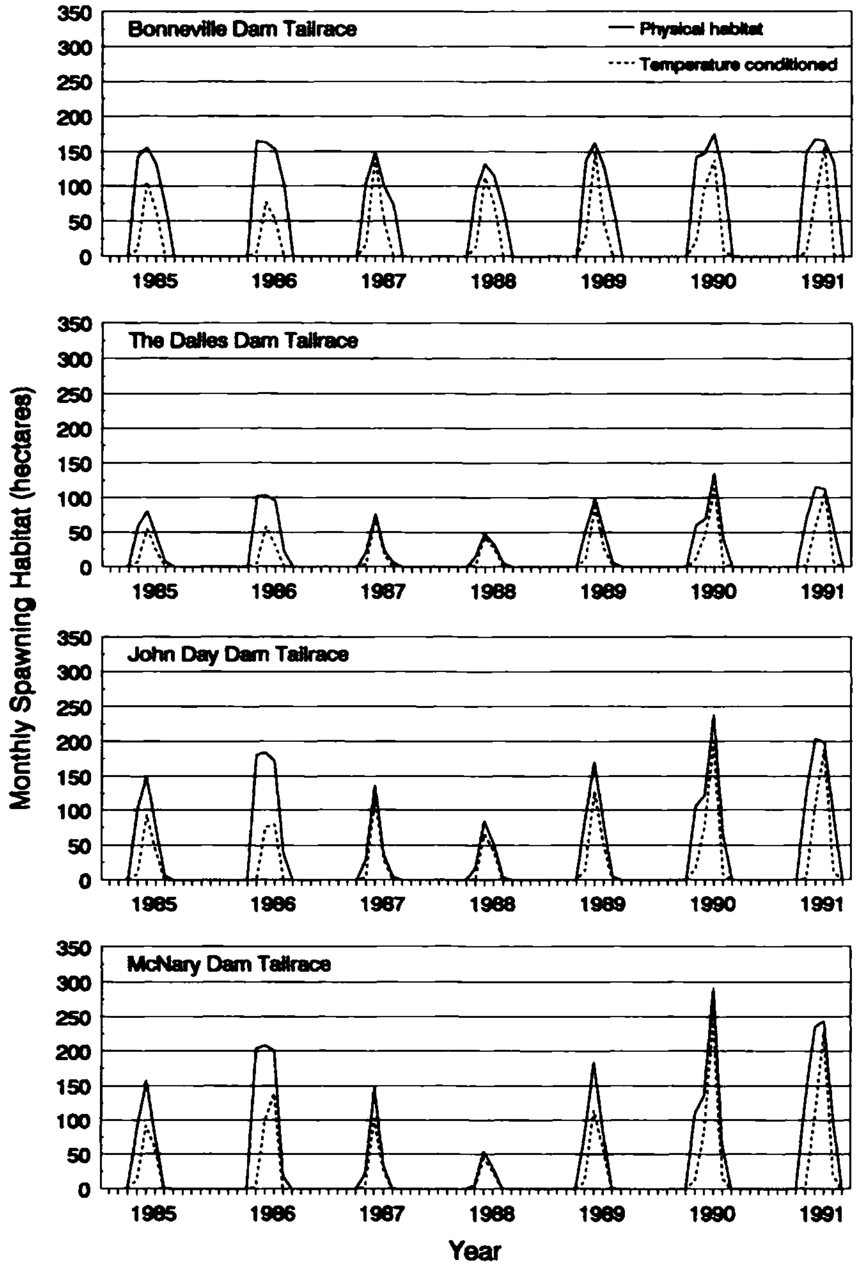

FIGURE 9.—Monthly weighted usable area present in the tailraces of Bonneville, The Dalles, John Day, and McNary dams during 1985–1991. Solid lines portray suitable microhabitat, dashed lines incorporate the suitability of daily water temperatures that occurred in each tailrace and therefore represent total habitat. Ascending limbs of the microhabitat (solid lines) are in April of each year; descending limbs are in July.

Rearing Habitat

The impounded river reaches have proportionately more rearing habitat than the unimpounded lower river reach (Table 3). Ranking the usable area of each river reach into high-, medium-, and low-quality habitat categories showed that differences exist in the amount and quality of the habitat for young-of-the-year and juvenile white sturgeons among the four reaches. The John Day Pool generally has more habitat for young of the year and

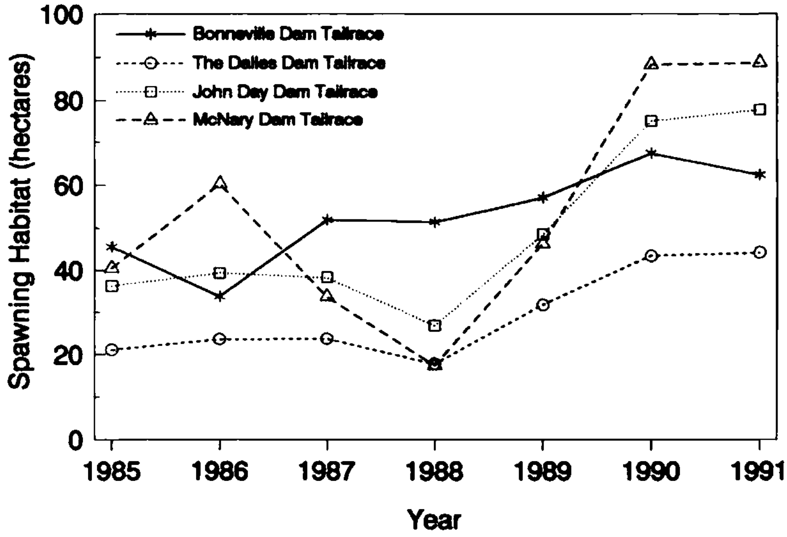

FIGURE 10.—Composite index of annual weighted usable spawning habitat present in the tailraces of Bonneville, The Dalles, John Day, and McNary dams. The composite index was calculated by multiplying average monthly values of total habitat by the number of days in the month, summing those, and dividing the sum by the number of days during April, May, June, and July.

juveniles than the other reaches, including the unimpounded lower river.[2]

Discussion

The relations between discharge and spawning habitat show that the operation of the hydropower system can have large effects on the spawning habitat of white sturgeon. Hydropower production has reduced spring and summer discharges (Figure 4; Ebel et al. 1989), and construction of the dams

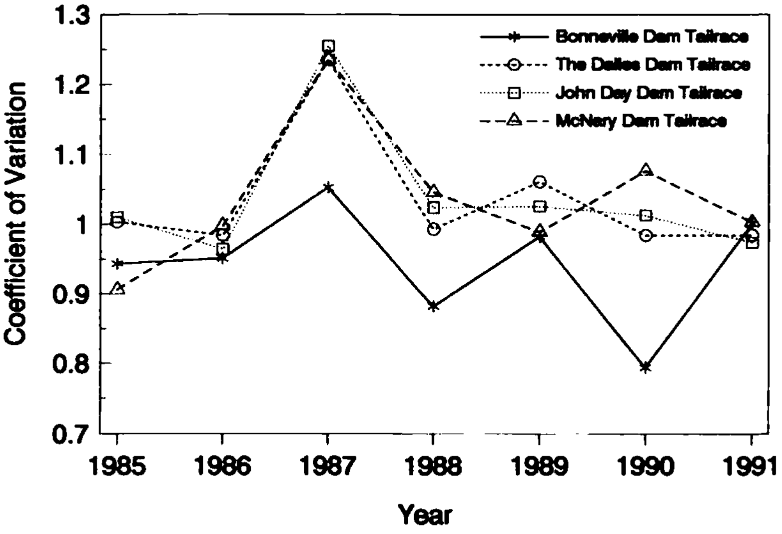

FIGURE 11.—Coefficient of variation (100·SD/mean) in weighted usable spawning area over time in the tailraces of Bonneville, The Dalles, John Day, and McNary dams.

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[2] Maps depicting the quality and physical location of rearing habitat for white sturgeons are available in digital format from the National Biological Survey. Contact the lead author for available formats.

TABLE 3.—Amount of habitat (defined by depth and substrate) for young-of-the-year and juvenile white sturgeon in the four Columbia River reaches downstream from McNary Dam. Areas are expressed in hectares; numbers in parentheses are percents of the total surface area.

Habitat	Lower river	Bonneville Pool	The Dalles Pool	John Day Pool
Young of the year				
Total surface area	25,629	7,632	3,639	19,781
Usable area	13,744 (54%)	5,935 (78%)	2,700 (74%)	14,727 (74%)
High quality[a]	6,477 (25%)	3,100 (41%)	633 (17%)	10,206 (52%)
Medium quality[b]	3,779 (15%)	1,870 (25%)	1,759 (48%)	3,422 (17%)
Low quality[c]	3,488 (14%)	965 (13%)	309 (8%)	1,099 (6%)
Weighted usable area	9,132	4,257	1,667	11,752
Juveniles				
Total surface area	41,223	7,632	3,639	19,781
Usable area	23,090 (56%)	6,618 (87%)	3,442 (95%)	17,277 (87%)
High quality[a]	7,791 (19%)	3,218 (42%)	1,542 (42%)	10,586 (54%)
Medium quality[b]	5,219 (13%)	1,752 (23%)	850 (23%)	4,077 (21%)
Low quality[c]	10,080 (24%)	1,648 (22%)	1,050 (29%)	2,614 (13%)
Weighted usable area	12,699	4,487	2,223	13,413

[a] Suitability 0.001 to 0.40.

[b] Suitability 0.41 to 0.80.

[c] Suitability 0.81 to 1.0.

inundated several rapids and falls that probably provided spawning habitat. During years of reduced river runoff, the lack of high-quality spawning habitat in the impounded reaches may preclude successful reproduction by white sturgeons. Recruitment to young of the year in the three impounded areas was poor during 1987–1989, when river discharges were low, and improved with the increased discharges during 1990 and 1991 (Table 4). Model output predicted lower amounts of spawning habitat during 1987–1989 relative to that predicted during 1990 and 1991 (Figure 9).

TABLE 4.—Mean catch of young-of-the-year white sturgeon per hectare of sampled bottom in four Columbia River reaches, as indicated by catches with bottom trawls. Data are from unpublished studies conducted from 1987–1991 by the authors and the National Marine Fisheries Service.

Reach and statistic	1988	1989	1990	1991
Lower river[a]				
Mean	0.53	2.15	4.99	4.75
SD	2.072	5.069	13.719	10.823
Number of tows	111	187	113	87
Bonneville Pool[b]				
Mean	0.00	0.33	2.11	6.85
SD		1.278	6.149	19.883
Number of tows	131	133	89	87
The Dalles Pool[b]				
Mean	0.00	0.00	0.26	1.85
SD			0.897	5.162
Number of tows	144	64	48	41
John Day Pool[b,c]				
Mean		0.00	0.00	0.07
SD				0.556
Number of tows		67	48	58

[a] The trawl used was a 7.9-m semiballoon shrimp trawl.

[b] The trawl used was a 4.9-m highrise shrimp trawl.

[c] John Day Pool was not sampled with bottom trawls during 1988.

The effects of river discharge, and thus hydropower system operation, on white sturgeon spawning habitat varies among areas. Bonneville Dam tailrace provides high-quality habitat for spawning white sturgeons at discharges lower than those needed to provide even low- to medium-quality habitat in the other three tailraces. The gradient of the water surface in the Bonneville Dam tailrace is greater than the gradient of the other tailraces (Figure 7), resulting in higher water velocities at low discharges. The lower gradients in tailraces of The Dalles, John Day, and McNary dams are a result of backwater effects from the downstream dams.

Though hydroelectric development has reduced the availability of habitat for spawning white sturgeons, it has increased the area suitable for young of the year and juveniles in the impounded reaches. Impoundment has increased water depths upstream from the dams; thus, because young-of-the-year and juvenile white sturgeons use the deeper water, the physical rearing habitat has increased. However, trawl catches of young-of-the-year and juvenile white sturgeon indicate that the rearing habitat in the impounded reaches is underused. Successive year-class failures and low numbers of recruits to young of the year during years of successful spawning have resulted in fewer fish to occupy the available habitat in these reaches (Table 4).

Our estimates of spawning and rearing habitat result from the unique application of two methodologies, PHABSIM and GIS. The hydraulic simulation model within the PHABSIM that was used to predict water velocities is generally accepted as adequate for use on smaller rivers and streams, but has never been applied to a river as large as the Columbia. The model outputs obtained were within acceptable ranges, and in theory the model is suitable for use on rivers this size.

Uncertainties in our estimates of habitat arise from the criteria curves that defined the spawning and rearing habitat, the functions used to obtain a composite suitability index, the area encompassed by transects (spawning habitat), and the accuracy of the base maps used in the GIS (rearing habitat). The criteria curves we used were developed from data collected within the study area, and represent the best information on habitat use by white sturgeon. The data depict habitat use under current environmental conditions caused by hydroelectric operations, not predevelopment conditions, and the effects on the analysis are unknown. Curves detailing habitat use in free-flowing rivers are needed; however, little free-flowing habitat with viable white sturgeon populations remains in the Columbia River basin.

We used the lowest value of the three habitat descriptors (lowest limiting parameter) as the CS to estimate spawning habitat because the area of suitable water depths and substrates within the known spawning areas of each river reach is not appreciably affected by varying river discharges, whereas water velocities are greatly affected. Calculation of spawning WUA with a multiplicative function slightly lowered the estimates of spawning habitat (National Biological Survey, unpublished data). We used the geometric mean of the suitabilities for water depth and substrate to derive a CS for young-of-the-year and juvenile white sturgeon because we had no evidence that any one physical habitat variable was more important than another. Water velocities at different river discharges were assumed suitable because young of the year and juveniles use mean column velocities from 0 m/s to near 2 m/s, and most of the study area has velocities within this range.

We used the best available maps of water depths and substrates to assess rearing habitat, but recent changes due to dredging, filling, and sediment deposition were not included. The maps also depict water depths at fixed river elevations. Water elevations fluctuate markedly in the upper end of the lower river reach, and the amount of habitat available for young-of-the-year and juvenile white sturgeon changes as river elevations rise and fall, but the areas are small compared with the total area of the lower river reach.

This analysis revealed that river discharge influences white sturgeon spawning habitat and that abundant physical rearing habitat exists in the impoundments. Spawning habitat could be increased through any of several actions. Increasing the discharge by restoring a more natural hydrograph during the white sturgeon spawning period would improve the reproductive success of the impounded populations, if the populations have not been overexploited (Reiman and Beamesderfer 1990) and enough spawners remain to use the habitat. Spawning areas might also be improved by physically altering the river channels to increase water velocities at low discharges (Khoroshko and Vlasenko 1970). Lowering reservoir elevations would increase the water surface gradient, resulting in increased water velocities and spawning habitat. There is evidence that the rearing habitat in the impounded reaches could biologically support more rearing white sturgeons. These fish feed primarily on benthic invertebrates obtained from the substrate and drifting in the currents (Schreiber 1962; Muir et al. 1988; McCabe et al. 1993). Densities of benthic invertebrates were higher in The Dalles Pool than densities in the unimpounded lower river reach (McCabe et al. 1993; National Biological Survey, unpublished data), and mean length-at-age for younger fish (1–5 years) is greater in the impounded areas than in the unimpounded lower river (National Biological Survey, unpublished data), suggesting greater food availability. These findings indicate that stocking or transplanting young fish into the impounded areas has potential for increasing the populations that have had poor reproductive success. If recruitment can be bolstered or the populations supplemented with young fish, and if overharvest is controlled, the white sturgeon populations in the impoundments could improve.

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Appendix: Transect Data

TABLE A.1.—Information on individual transects used in the PHABSIM analysis of white sturgeon spawning habitat in the lower Columbia River.

						Water elevation–discharge pairs		
Transect	Number of verticals	Width (m)	Calibration discharge (m^3/s)	Reach length (m)	Percent of total length	Number	Range of water elevations (m)	Range of discharges (m^3/s)
Bonneville Dam tailrace								
1	35	457	6,995	877	13.8	6	2.68–6.19	3,598–9,994
2	30	694	6,502	1,604	25.3	7	2.80–6.52	3,590–9,564
3	19	442	6,505	1,444	22.8	5	3.11–6.95	3,590–9,994
4	18	308	6,588	1,260	19.9	5	4.18–7.56	4,527–9,957
5	23	344	7,301	1,152	18.2	6	3.75–7.83	3,632–9,957
The Dalles Dam tailrace								
1	29	572	4,811	144	1.9	5	22.86–24.61	3,891–10,294
2	17	369	4,868	706	9.1	6	22.88–24.63	4,721–10,294
3	19	354	4,842	1,936	25.0	8	22.92–24.70	3,583–10,342
4	20	367	4,980	1,673	21.6	9	22.95–24.37	3,659–9,383
5	20	713	3,817	1,129	14.6	5	22.88–24.78	2,508–9,127
6	34	904	4,699	961	12.4	4	22.89–24.72	3,785–9,207
7	29	594	4,390	899	11.6	4	23.31–25.07	3,930–9,207
8	27	802	4,926	310	4.0	6	23.17–25.40	4,479–9,785
John Day Dam tailrace								
1	36	520	3,160	1,136	16.5	7	48.37–49.19	2,942–9,488
2	35	728	2,884	2,239	32.5	5	48.34–49.23	2,922–9,032
3	44	774	4,002	2,298	33.4	6	48.52–49.53	2,356–9,145
4	62	834	4,614	862	12.5	5	48.52–49.53	2,520–9,317
5	45	846	4,071	347	5.1	5	48.52–49.68	2,528–9,317
McNary Dam tailrace								
1	33	1,214	3,824	607	8.2	14	80.83–81.63	2,610–9,912
2	32	1,165	3,336	1,860	25.0	13	80.83–81.69	3,465–9,912
3	24	901	3,301	1,958	26.3	13	81.02–81.75	3,196–9,912
4	33	929	3,943	1,045	14.1	15	81.11–81.72	3,536–9,858
5	23	524	3,613	853	11.5	14	81.02–81.81	2,610–8,012
6	30	1,054	3,891	813	10.9	14	81.17–81.84	3,562–8,014
7	29	782	5,235	297	4.0	15	81.23–81.84	2,322–8,041