

## Upstream Swimming Performance of Adult White Sturgeon: Effects of Partial Baffles and a Ramp

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**Abstract.**—The upstream passage of sturgeon (family Acipenseridae) past barriers such as dams has become a concern of fisheries managers in California. Knowledge about the swimming abilities of adult sturgeon species, particularly with relationship to fish ladders, is limited. Wild adult white sturgeon *Acipenser transmontanus* ( $n = 25$ ; total length, 135–198 cm) captured in the San Francisco Estuary and Yolo Bypass toe drain were swum in a variable-speed aluminum flume (24.4 m long  $\times$  2.1 m wide  $\times$  1.4 m deep) to evaluate swimming behavior around simulated fish-ladder-type partial baffles. Four baffle types (one horizontal ramp and three different vertical slot designs) set in two configurations were tested at three velocity regimes (velocity range around baffles, 0.28–2.52 m/s). In general, faster velocities (0.76–1.07 m/s) cued fish to swim upstream sooner ( $\leq 100$  s). Among the baffle types, the percentage of successful passage was variable, and no statistically significant pattern was detected. The tail-beat frequency of fish significantly increased in the high-velocity (to 2.52 m/s) regions of the flume adjacent to the energy-dissipating baffles, where sturgeon were able to pass by swimming in bursts, followed by a resting and recovery period in slower water. Successful white sturgeon passage structures should incorporate rapid-velocity (e.g., 0.84–2.52-m/s) sections between somewhat slower (e.g., 0.51–0.68-m/s) sections for rest and recovery.

River modifications (e.g., dams) that block spawning migration routes present a variety of problems for diadromous fishes. Most upstream passage facilities, such as fish ladders, have been designed for salmonid species, but the swimming patterns of sturgeon (family Acipenseridae) differ from those of salmonids (Webb 1975, 1986; Lauder 2000; Cech and Doroshov 2004). Populations of the world's 24 species of sturgeon and paddlefish (family Polyodontidae) are low or declining rapidly (Jennings and Zigler 2000; Van Winkle et al. 2002). Blocked historic migratory routes and inaccess-

sibility to suitable spawning habitat are among the greatest contributors to the population declines of most sturgeon species (Auer 1996).

Reductions in river flow also present problems affecting sturgeon species' upstream migration and successful spawning. In the Sacramento River, California, increased flow stimulated the upstream movements of prespawning adult white sturgeon *Acipenser transmontanus* up to 25 km/d. These fish tended to cease their upstream migration or drift downstream when flows decreased below 150 m<sup>3</sup>/s (Schaffter 1997). Changes in velocities and flows affect white sturgeon migration behavior; therefore, proper flow management is crucial to the survival of the sturgeon population (Kohlhorst et al. 1991). There may have

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been, for example, a larger spawning population in California's central valley watersheds before diversion of much of the San Joaquin River flow for agricultural irrigation (Moyle 2002).

Recent interest in restoring sturgeon species' migration routes (e.g., via sturgeon-appropriate fish passage structures) has stimulated research to help design sturgeon passage facilities. Baffles are required in fish passage structures that include a hydrostatic head in order to dissipate some of the energy associated with water flowing down a slope. Because of sturgeons' demersal cruising, "nonjumping" locomotion, the baffle design in a sturgeon-appropriate fish passage structure will differ from that in many fish passage structures installed for migrating salmonids. The purpose of this study was to investigate the swimming performance and current attraction velocities of adult white sturgeon around simulated fish passage baffles in a laboratory swimming flume.

### Methods

*Fish collection, holding, and disposition.*—Adult white sturgeon ( $n = 18$ ; total length [TL], 135–198 cm; mass, 16–40.5 kg) were captured in the San Pablo Bay and Carquinez Straits regions of the San Francisco Estuary, California (temperature, 11–15°C; salinity, 0–9‰) with rod-and-reel gear. Adult fish ( $n = 7$ ; TL, 143–164 cm; mass, 18.6–25.6 kg) were also collected from the Yolo Bypass flood conveyance toe drain (temperature, 15.5°C; salinity, 0‰) near Sacramento, California, using a fyke trap operated by the California Department of Water Resources (CDWR). The toe drain is a perennial channel on the eastern edge of the Yolo Bypass (engineered floodplain), which carries floodwater mainly from the Sacramento and Feather rivers to the San Francisco Estuary during high-flow events. This toe drain supports white sturgeon migration up the Sacramento River for spawning (Sommer et al. 2001). Fish were collected during their migration season between 21 January and 23 May 2003 (Kohlhorst et al. 1991). After quick (0.5–1.0 h) transport from the collection location in a trailer-mounted oxygenated tank containing water from the collection site, fish were held at the University of California–Davis (UC Davis) J. Amorochio Hydraulics Laboratory in 3-m diameter (15-m<sup>3</sup>) circular flow-through (0.1 L/s replenishment) tanks at  $14 \pm 1^\circ\text{C}$  and 0‰ salinity. Fish were allowed to acclimate for 3 d from the capture date before they were used in swimming experiments, but they were held for only short periods (mean, 11 d) without feed for experiments before they were returned to the collection site. This starvation period was assumed not to influence the passage performance of fish, considering sturgeon

species' fasting behavior before and during their spawning migration (Dadswell et al. 1984; Sulak and Randall 2002). To test the possible learning behavior of fish with regard to the structures, some fish were used in as many as three experiments with no fewer than 2 d between experiments. Some tagged white sturgeon made repeated transits of the Dalles Dam (Columbia River, U.S. Army Corps of Engineers, Portland [Oregon] District) during a year, using the same fishway for each upstream ascent (M. Parsley, U.S. Geological Survey, personal communication). The 2-d (minimum) recovery time between experiments and 3-d acclimation time after capture were considered adequate, based on plasma cortisol and lactate measurements on five fish, which were indistinguishable from preexercise levels 24 h after similar sturgeon passage experiments in the same flume (D. Cocherell and coworkers, UC Davis, unpublished data). Fish from the estuary were assumed to be acclimated to the freshwater before their first experiments, considering the low (hyposmotic to isosmotic) salinity level (0–9‰) to which fish were presumably acclimated at capture (M. McEnroe, State University of New York, and J. J. Cech, unpublished data).

*Experimental flume and hydraulic conditions.*—Swimming experiments were carried out in a variable-speed aluminum flume (24.4 m long  $\times$  2.1 m wide  $\times$  1.4 m deep). While the flume was operating, a constant volume of water was continuously pumped from a temperature-controlled ( $\pm 1^\circ\text{C}$  of fish-holding tank temperature) underground reservoir into a head tank that fed the flume. Water depth and velocity were controlled by opening or closing a tailgate at the downstream end of the flume.

Hydraulic structures within the flume (fixed at 0% bed slope) consisted of two configurations (Figure 1), simulating baffles that might be used in a sturgeon passage structure. Four baffle types (one horizontal ramp and three different vertical slot designs) set in two configurations were tested. The vertical–vertical (VV) configuration consisted of an upstream vertical baffle that concentrated flow in the center of the flume (two laterally placed vertical barriers with a central channel of 103-cm width) and a downstream vertical baffle that was centered in the flume, concentrating flow between the baffle and the flume walls (two lateral channels of 60.5-cm width). The horizontal–vertical (HV) configuration included an upstream vertical baffle (two laterally placed vertical barriers with a central channel of 68-cm width) and a downstream ramp at 12.5% slope that peaked at 30.5-cm height (spanning the width of the flume, with 2.4-m-long ramps attached on the upstream and downstream sides of the peak).

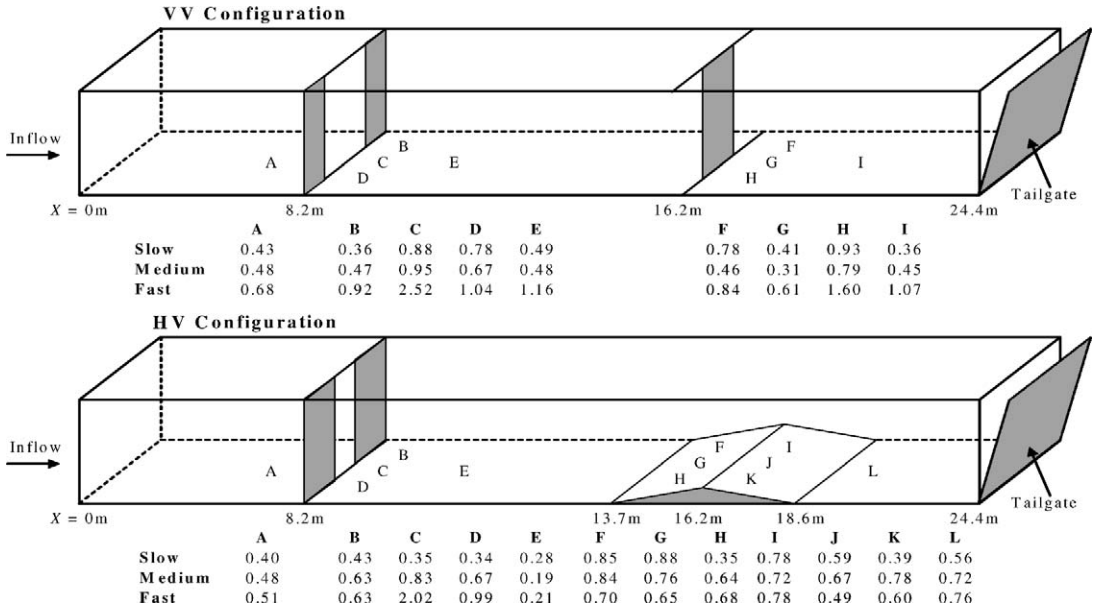


FIGURE 1.—Three-dimensional views of the vertical-vertical (VV) and horizontal-vertical (HV) configurations with depth-averaged velocities (m/s) in the lettered areas of interest at slow, medium, and fast treatments. The tailgate, which controlled flume water depth and velocity, comprised most of the downstream wall of the flume. In the VV configuration, the slot widths at 8.2 and 16.2 m were 1.03 m and 0.605 m, respectively. The HV configuration slot width at 8.2 m was set to 0.68 m and the ramp at 12.5% slope.

*Experimental procedures.*—At the beginning of each experiment, fish were transported via a wet transport sling from their holding tank to a 3-m × 2.1-m section at the downstream end of the flume, confined to the flume section by a plastic mesh crowder, and allowed to acclimate for 30 min. Continued gill irrigation during transportation (30–60 s) to the flume minimized the struggling of sturgeon in the sling. Swimming experiments included three 10-min trials at different water velocities: first at “slow” and then at randomly ordered “medium” and “fast” water velocity conditions (Figure 1). The peak depth-averaged velocities (maximum velocities from 28 measurements throughout the water column measured with a SonTek 10-MHz Laboratory Acoustic Doppler Velocimeter) of the three different velocity conditions in the areas of interest for VV and HV configurations are shown in Figure 1. In some areas of the flume, higher peak, depth-averaged velocities were measured at “slower” conditions because backflow occurred in areas around the baffles and tailgate (downstream end of the flume). Velocity for the VV configuration was high in regions at baffle openings and at the downstream end of the flume. The HV configuration showed higher velocities at the upstream vertical baffle opening, became very slow in the midflume region,

increased over the downstream horizontal ramp, and remained high until the downstream region.

At the beginning of each experiment, the crowder was removed and the time needed for fish to swim upstream and pass the two baffles was measured. Between each velocity trial, fish were gently guided to the downstream end of the flume using long-handled dip nets, confined by the crowder, and given a 2-min rest period before beginning the next velocity trial. During the experiment, the location of fish and the tail-beat frequency (TBF) were observed and recorded (strokes/min) every 30 s. Total length was recorded for all fish, and the live mass was measured for most fish at the end of the experiment.

*Data and statistical analyses.*—The swimming performance of fish around the baffles was evaluated as either “successful” (fish passed the baffles) or “unsuccessful” (fish did not pass the baffles). A repeated-measures analysis of variance (ANOVA) on ranks was used to analyze these data, and the times taken to pass the baffles were analyzed by two-way ANOVA (with velocity and baffle types as factors). The time to pass the first baffle was measured from start of a velocity segment to the first baffle passage, and the time to pass the second baffle was measured from the first baffle passage to the second baffle passage. Finally, a mixed-model ANOVA was used to

TABLE 1.—Percentage of white sturgeon passing partial baffles in two different configurations (VV = vertical–vertical [ $n = 31$ ]; HV = horizontal–vertical [ $n = 9$ ]) at three velocities (see Figure 1) tested at University of California–Davis, spring 2003.

Velocity	Percentage passing first baffle		Percentage passing second baffle	
	VV	HV	VV	HV
Slow	48	44	29	22
Medium	74	11	61	11
Fast	71	78	55	11

evaluate differences in TBF among the velocity regimes and among five flume sections: downstream, downstream baffle, midflume, upstream baffle, and upstream. All values were considered statistically significant at  $\alpha = 0.05$ . Thirty-one experiments were completed with the VV baffle configuration and nine experiments with the HV configuration. An additional seven experiments in the VV configuration and two experiments in the HV configuration were ended prematurely and removed from the analyses because sturgeon impinged at the downstream end of the flume. All of the impingement events were repeatedly exhibited by the same seven fish and were not related to the number of experiments in which fish were used.

### Results

Although some fish were used as many as three times in the experiments (six fish were used one time each in VV; five fish were used two times each in VV; seven fish were used two times each in VV and one time each in HV; and four fish were used one time each in VV and one time in HV), there was no significant correlation between swimming performance and the number of experiments in which fish were used ( $P = 0.99$ ). Therefore, no training effect resulting from multiple encounters between the fish and the structures was detected. Also, there were no significant correlations between swimming performance and capture location ( $P = 0.609$ ) or number of days in captivity ( $P = 0.476$ ).

#### VV Baffle

The percentage of successful passage through the downstream baffle with the VV configuration trended lower at the slow velocity (48%) than at either the medium (74%) or fast velocity (71%) (Table 1), although these relationships were not found to be significant (mixed-model ANOVA; slow versus medium:  $q = 2.726$ ,  $df = 2$ ,  $P > 0.05$ ; slow versus fast:  $q = 2.922$ ,  $df = 2$ ,  $P > 0.05$ ). Successful passage of the upstream baffle was significantly lower at slow (29%

TABLE 2.—Mean (SE) time taken (s) for white sturgeon to pass partial baffles in two different configurations at three velocities. Depth-averaged velocities in various parts of the flume are shown in Figure 1; n.a. = not available. See Table 1 for additional details.

Velocity	First baffle		Second baffle	
	VV	HV	VV	HV
Slow	133 (45)	283 (118)	243 (71)	118 (58)
Medium	75 (24)	14 (n.a.)	117 (29)	37 (n.a.)
Fast	83 (26)	48 (12)	100 (27)	38 (n.a.)

passing) velocity than at both medium (61%;  $q = 4.174$ ,  $df = 2$ ,  $P < 0.05$ ) and fast (55%;  $q = 4.311$ ,  $df = 2$ ,  $P < 0.05$ ) velocities. Accordingly, significantly fewer fish successfully passed the upstream baffle than passed the downstream baffle at slow velocity ( $q = 4.572$ ,  $df = 2$ ,  $P < 0.05$ ), but there was no significant difference in upstream versus downstream baffle passage percentage at either medium ( $q = 2.155$ ,  $df = 2$ ,  $P > 0.05$ ) or fast ( $q = 2.694$ ,  $df = 2$ ,  $P > 0.05$ ) velocity. The offset (nonaligned) slots of the two baffles in the VV baffle configuration (Figure 1) resulted in many sturgeon accelerating, in a straight-line burst, through the downstream slot and impacting the upstream baffle, slowing their passage past the two baffles.

#### HV Baffle

Only 44% passed the downstream horizontal baffle (ramp) at slow velocity, 11% (one fish) at medium, and 78% at fast, whereas 22% passed the upstream vertical baffle at slow and 11% (one fish) at each of medium and fast velocities. Although significant differences ( $\chi^2 = 20.952$ ,  $df = 5$ ,  $P < 0.001$ ) were detected for successful passage among velocities, pairwise comparisons (Student–Newman–Keuls test) of groups were unable to distinguish differences among velocities. This is probably due to the smaller sample size used in the HV configuration, and because so few fish (1 of 9) successfully passed both baffles at the medium and fast velocities.

#### Both Baffle Types

Data collected across both baffle types were combined and the mean time taken to pass baffles was always greatest ( $F = 3.782$ ,  $df = 2$ ,  $P = 0.026$ ) at slow velocity than at either medium or fast velocity (Table 2). Furthermore, no significant difference ( $F = 2.351$ ,  $df = 3$ ,  $P = 0.076$ ) was found in the amount of time taken to pass both baffles between the two baffle configurations. On average, if a fish passed the first baffle in the VV configuration it would also pass the

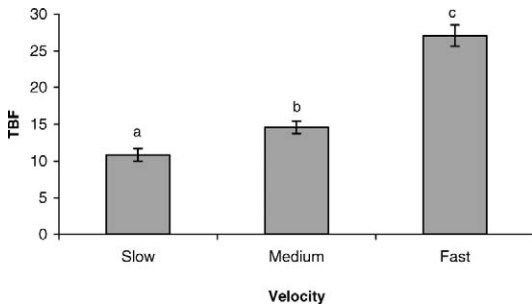


FIGURE 2.—Mean  $\pm$  SE tail-beat frequencies (TBFs) of 25 adult white sturgeon in 38 experiments tested at three velocities at the University of California–Davis during spring 2003 ( $n = 216, 167,$  and  $125$  measurements in the slow, medium, and fast treatments, respectively). Different letters above the bars indicate statistically distinguishable groupings ( $F = 65.71, df = 2, P < 0.001$ ).

second. This was not true for the HV configuration (Table 1).

Evaluation of TBF among the three velocity regimes and the five flume sections showed that TBF increased as water velocity increased in the flume ( $F = 65.71, df = 2, P < 0.001$ ; Figure 2). The TBF was also higher in both baffle sections compared with the upstream and downstream regions but was not significantly different from the midflume region (mixed-model ANOVA:  $F = 27.08, df = 4, P < 0.001$ ; Figure 3). Thus, sturgeon were swimming faster in the highest velocity regions of the flume, using higher TBF, to pass through the high-velocity slots adjacent to the energy-dissipating baffles. Fish used the midflume region for both resting and continued burst swimming, resulting in a high TBF variance, with the mean TBF indistinguishable from TBF in the two-baffle sections (Figure 3). The lower TBF exhibited in the downstream region was associated with what appeared to be “staging” behavior (i.e., searching activity to locate an optimal hydraulic “path” up the flume) before acceleration past the downstream baffle. In contrast, the lowest TBF exhibited in the upstream region included many “resting” (TBF = 0) data points, where many of the sturgeon oriented into the flow, on the bottom. There were no significant TBF differences between the two baffle configurations.

### Discussion

Sturgeon species may be unable to use fishways designed for salmonids because sturgeon and salmon are morphologically very different from each other. Webb (1986) ascribed the poorer swimming performance of lake sturgeon *A. fulvescens* to its increased pressure drag, which is associated with the large scutes along the body, and decreased thrust from the reduced

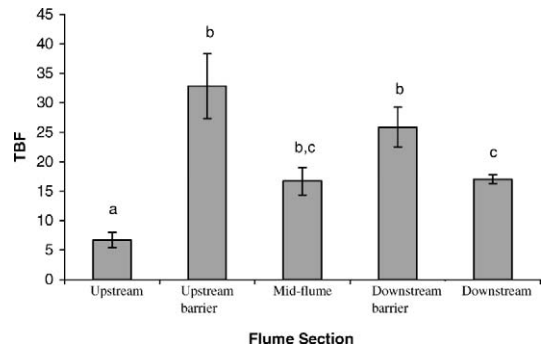


FIGURE 3.—Mean  $\pm$  SE tail-beat frequencies (TBFs) of 25 adult white sturgeon in 38 experiments at the University of California–Davis during spring 2003, grouped by flume section. Different letters above the bars indicate statistically distinguishable groupings ( $F = 27.08, df = 4, P < 0.001$ ).

tail depth and nonossified skeleton. Although the white sturgeon can direct the force produced by its heterocercal tail (Liao and Lauder 2000), Peake et al. (1997) showed that the lake sturgeon can lose up to 18% of its thrust compared with similarly sized salmonids. Therefore, larger sturgeon may be more comparable in swimming performance to smaller salmonids (Peake et al. 1997).

Sturgeon passage and swimming performance have been investigated in other species. White and Mefford (2002) tested adult shovelnose sturgeon *Scaphirhynchus platyrhynchus* in multiple fishway designs, including a standard vertical slot (four slots), dual vertical slot (four chevron-shaped slots), and a rock fishway with a boulder pattern (velocity range, 0.76–1.2 m/s). They found that increased eddy size downstream of the barriers was associated with decreased passage success. Passage was more successful in the rock fishway, presumably because a variety of velocities were available, and adult shovelnose sturgeon seemed to search for the least challenging hydraulic conditions. Although this type of fishway provides a wide range of velocities that could benefit other migrating species, in addition to adult shovelnose sturgeon, we found that faster velocities generally cued adult white sturgeon to swim upstream in a shorter period of time. In our study, white sturgeon exposed to the slow velocity, on average, took the longest time to reach the upstream end of the flume. Often, at the faster velocities, sturgeon would “burst” to the upstream end. If the baffle slots were aligned, and the water velocities were not excessive (i.e.,  $>2.52$  m/s), white sturgeon passage might be even greater because their upstream swimming bursts were most effective in straight trajectories. Previous work on the swimming performance of adult

shovelnose sturgeon found the critical swimming velocity to be 1.16 m/s (Adams et al. 2003), while burst swimming of lake sturgeon was measured as 1.60 m/s (Peake et al. 1997). Our results for adult white sturgeon show that fish were able to pass baffles with water velocities as high as 2.52 m/s with TBF at approximately 33 strokes/min in these large fish. Peake et al. (1997) used lake sturgeon ranging in size from 106 to 132 cm, and they found that swimming endurance increased with the size of the fish. White sturgeon tested in our experiments were considerably larger, ranging from 135 to 198 cm, probably accounting for the higher swimming velocity, the highest measured for any sturgeon species.

Sturgeon were frequently observed holding in areas of our flume without any caudal movements (e.g., upstream section; Figure 3). They appeared to rely on their pectoral fins angled against the bottom, which had an anchoring effect. This behavior was also noted by Adams et al. (2003) in juvenile shovelnose sturgeon and juvenile pallid sturgeon *S. albus*. Flume studies conducted by White and Mefford (2002) showed that shovelnose and lake sturgeon could overcome high-velocity flows by combining sprints with short resting periods. Hurley et al. (1987) concluded that in the wild, shovelnose sturgeon are relatively sedentary and tend to prefer areas that have lower velocities. Their observations and flow measurements were confirmed by Adams et al. (1997), who discovered that adult shovelnose sturgeon favored the same flows when swum in a flume. Although burst swimming can allow sturgeon to pass through smaller areas of high velocity, using this pectoral fin anchoring method of sustained holding in high velocities may be an important part of successful upstream passage.

Adult white sturgeon were able to pass the partial baffle configurations, especially at a faster water velocity with its increased attraction flow. However, the percentage decreased when passing the H baffle (medium velocity) and the V baffle when combined with the downstream H baffle (all velocity regimes). These decreased passage percentages possibly resulted from unstable hydraulic conditions caused by eddies and turbulence near the H baffle and the tailgate. For example, two of the three peak, depth-averaged velocities across the ramp incline of the H baffle were actually the fastest during the medium water velocity (Figure 1). Also, several fish were observed to hold position either downstream of the H baffle or on its ramp incline instead of swimming upstream. Therefore, white sturgeon might have difficulty negotiating the sharp peak of the ramp, especially when water velocity was high (during medium velocity). Although sturgeon readily ascended the ramp incline, redesigning the

ramp exit and minimizing turbulence at or around a horizontal baffle may improve their passage in future experiments. The better passage success measured with the VV configuration probably resulted from more stable and uniform hydraulic conditions as compared with those associated with the HV configuration. Also, the wider slot width between the upstream baffles in the VV configuration probably facilitated passage compared with the narrower vertical slot in the HV configuration. Parsley et al. (2006) also found that many more adult white sturgeon ascended the east fishway, which has a wider slot than the north fishway, at the Dalles Dam on the Columbia River.

In summary, adult white sturgeon (TL, 135–198 cm) were stimulated to swim upstream by water velocities of 0.45 m/s or more, reaching swimming velocities exceeding 2.52 m/s by undulating their bodies at approximately 33 strokes/min. They swam approximately 20 m, past two partial baffles, within 100 s (mean) at the fastest water velocities. Sturgeon swimming was typified by those swimming bursts, which were followed by protracted rest and recovery periods, oriented into the current on the bottom. Successful adult white sturgeon passage structures will probably incorporate rapid-velocity (e.g., 0.84–2.52-m/s) sections between somewhat slower (e.g., 0.51–0.68-m/s) sections for rest and recovery. Further research should incorporate longer-term investigations with larger sample sizes, including some during nighttime periods in the dark.

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### References

- Adams, S. R., G. L. Adams, and G. R. Parsons. 2003. Critical swimming speed and behavior of juvenile shovelnose sturgeon and pallid sturgeon. *Transactions of the American Fisheries Society* 132:392–397.
- Adams, S. R., G. R. Parsons, J. J. Hoover, and K. J. Killgore. 1997. Observations of swimming ability in shovelnose sturgeon (*Scaphirhynchus platyrhynchus*). *Journal of Freshwater Ecology* 12:631–633.
- Auer, N. A. 1996. Importance of habitat and migration to sturgeons, with emphasis on lake sturgeon. *Canadian Journal of Fisheries and Aquatic Sciences* 53:152–160.

- Cech, J. J., Jr., and S. I. Doroshov. 2004. Environmental requirements, preferences, and tolerance limits of North American sturgeons. Pages 73–83 in F. W. H. Beamish, G. T. O. LeBreton, and R. S. McKinley, editors. *Biology of North American sturgeon and paddlefish*. Kluwer, Dordrecht, The Netherlands.
- Dadswell, M. J., B. D. Taubert, T. S. Squiers, D. Marchette, and J. Buckley. 1984. Synopsis of biological data on shortnose sturgeon, *Acipenser brevirostrum* LeSueur 1818. FAO (Food and Agriculture Organization of the United Nations) Fisheries Synopsis 140:1–45.
- Hurley, S. T., W. A. Hubert, and J. G. Nickum. 1987. Habitats and movements of shovelnose sturgeons in the upper Mississippi River. *Transactions of the American Fisheries Society* 116:655–662.
- Jennings, C. A., and S. J. Zigler. 2000. Ecology and biology of paddlefish in North America: historical perspectives, management approaches, and research priorities. *Reviews in Fish Biology and Fisheries* 10:167–181.
- Kohlhorst, D. W., L. W. Botsford, J. Brennan, and G. M. Cailliet. 1991. Aspects of the structure and dynamics of an exploited central California population of white sturgeon (*Acipenser transmontanus*). Pages 277–294 in P. Williot, editor. *Acipenser: actes du Premier Colloque International sur l'Esturgeon*. [*Acipenser: proceedings of the First International Colloquium on Sturgeon*.] Centre d'Etudes du Machinisme Agricole, du Rural, des Eaux et Forêts, Bordeaux, France.
- Lauder, G. V. 2000. Function of the caudal fin during locomotion in fishes: kinematics, flow visualization, and evolutionary patterns. *American Zoologist* 40:101–122.
- Liao, J., and G. V. Lauder. 2000. Function of the heterocercal tail in white sturgeon: flow visualization during steady swimming and vertical maneuvering. *Journal of Experimental Biology* 203:3585–3594.
- Moyle, P. B. 2002. *Inland fishes of California*. University of California Press, Berkeley.
- Parsley, M. J., C. D. Wright, B. K. van der Leeuw, E. E. Kofoot, C. A. Perry, and M. L. Moser. 2006. Behavior of white sturgeon near hydroprojects and fishways. Report of the U.S. Geological Survey, Western Fisheries Research Center, Idaho Cooperative Fish and Wildlife Research Unit, and National Marine Fisheries Service, Northwest Fisheries Science Center, to the U.S. Army Corps of Engineers, Portland, Oregon.
- Peake, S., F. W. H. Beamish, R. S. McKinley, D. A. Scruton, and C. Katopodis. 1997. Relating swimming performance of lake sturgeon, *Acipenser fulvescens*, to fishway design. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1361–1366.
- Schaffter, R. G. 1997. White sturgeon spawning migrations and location of spawning habitat in the Sacramento River, California. *California Fish and Game* 83:1–20.
- Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer, and L. Schemel. 2001. California's Yolo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* 26(8):6–16.
- Sulak, K. J., and M. Randall. 2002. Understanding sturgeon life history: enigmas, myths, and insights from scientific studies. *Journal of Applied Ichthyology* 18:519–528.
- Van Winkle, W., P. J. Anders, D. H. Secor, and D. A. Dixon. 2002. *Biology, management, and protection of North American sturgeon*. American Fisheries Society, Symposium 68, Bethesda, Maryland.
- Webb, P. W. 1975. Acceleration performance of rainbow trout *Salmo gairdneri* and green sunfish *Lepomis cyanellus*. *Journal of Experimental Biology* 63:451–465.
- Webb, P. W. 1986. Kinematics of lake sturgeon, *Acipenser fulvescens*, at cruising speeds. *Canadian Journal of Zoology* 64:2137–2141.
- White, R. G., and B. Mefford. 2002. Assessment of behavior and swimming ability of Yellowstone River sturgeon for design of fish passage devices. Report of the Montana Cooperative Fishery Research Unit, Montana State University, Bozeman, and the U.S. Bureau of Reclamation, Water Resources Research Laboratory, Denver, to the U.S. Army Corps of Engineers, Omaha, Nebraska.