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Paddlefish and Sturgeon Entrainment by Dredges: Swimming Performance as an Indicator of Risk

BACKGROUND: Paddlefish and sturgeons (*Acipenseriformes*) collectively constitute one of the most imperiled groups of fishes in North America. Populations were over-exploited for meat and caviar in the early 20th century (Tower 1908, Stockard 1908, Saffron 2002) and are impacted today by continued harvesting, habitat degradation, and habitat loss (Williamson 2003). Some instances of entrainment have been documented by observers on coastal dredges, but effects of entrainment on adult fish are presumed low.[1]

Recently, resource agencies have expressed concern that inland dredging may impact populations of some species by entraining juveniles. Small young-of-year fish (<200 mm) are believed to be especially susceptible. Entrained fishes would likely go undetected during normal dredging operations because dredged material discharges are not monitored and because the remains of these largely cartilaginous fishes, especially very small individuals, may be unrecognizable. Risk of entrainment, however, could be estimated by comparing the suction velocities generated by dredges, or "flow fields," with swimming performance data for these fishes. Measures of swimming performance include:

- Rheotaxis, "the response or reaction of an organism to the stimulus of a current" (Tweeny and Hughes 1967).
- Endurance, the time that an organism can continue to move or maintain position.
- Behavior, overt actions of an organism in direct response to a stimulus.

Simplified models of flow fields exist (http://el.erdc.usace.army.mil/dots/doer/flowfields/dtb350.html), but data on swimming performance of small paddlefish and sturgeons are limited (Peake et al. 1997, Adams et al. 1999).

PURPOSE: The purpose of this study was to assess potential entrainment-related losses of paddlefish and sturgeons from dredging operations using measures of swimming performance as descriptors of risk.

LABORATORY METHODOLOGY: Species were selected representing a range of morphologies and conservation status. Paddlefish (*Polyodon spathula*) have a deeply forked caudal fin and a short, thick, naked peduncle. They are pelagic, continuous swimmers. Lake sturgeon (*Acipenser fulvescens*) have an asymmetrically forked caudal fin and a short, muscular, naked peduncle. They are demersal swimmers. Pallid sturgeon (*Scaphirhynchus albus*) have an asymmetrically forked caudal fin but, unlike lake sturgeon, possess a long, thin, armored

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[1] For the period 1990-2005, there are fewer than 25 confirmed instances of sturgeon entrainment by dredges operating in Gulf and Atlantic waters (unpublished data, Dena Dickerson, Research Biologist, U.S. Army Engineer Research and Development Center, Vicksburg, MS).

peduncle. They are also demersal swimmers but frequently rest directly on substrates. All three species are listed as threatened or endangered, but degree of imperilment varies among species and geographic regions (Table 1).

Table 1
Conservation Status of Three Acipenseriform Fishes[1]

Species	AFS	U.S.	States
Paddlefish	Vulnerable	None	Endangered (NY, NC, TX) Threatened (MN, OH, VA) Special concern (MS) Protected (LA, AL)
Lake sturgeon	Threatened	Management Concern	Endangered (TN, IN, OH, PA, IL, MO, IA) Threatened (NY, MI, NE) Special Concern (MN)
Pallid sturgeon	Endangered	Endangered	Not applicable - Federal status overrides state status

[1] Based on information from the American Fisheries Society (AFS), the federal government (US), and individual states (Warren et al. 2000; Scharpf 2005a, 2005b).

Juvenile fish were obtained from fish hatcheries and housed in closed-system, recirculating tanks, with weak (<5 cm/s) directional flow. Holding tanks were 1600-liter Ferguson flumes (lake sturgeon), 300-liter Model LS-510 Living Streams (paddlefish), and 400-liter Model LS-700 Living Streams (pallid sturgeon). Ferguson flumes have been described previously (Baker et al. 1994, Hoover et al. 1999), and information on Living Streams is available from the manufacturer (Frigid Units, Toledo, Ohio). Light-dark cycles approximated 12L:12D. Fish were fed two to four times daily: dry food, frozen bloodworms, frozen mosquito larvae (lake sturgeon); frozen bloodworms and frozen brine shrimp (paddlefish and pallid sturgeon). Fish were not fasted prior to testing. Individual fish were tested only once to avoid "training effects" (Parsons et al. 2003).

Tests were conducted in a 100-liter Blazka-type swim tunnel using protocol from a previous study of the federally endangered pallid sturgeon, *Scaphirhynchus albus* (Adams et al. 1999). Flow was generated by a motor-driven propeller and turbulence removed by collimators (flow filters) at the front end of the tunnel. Flow through the working section of the tunnel is straight and uniform (rectilinear). The section of the tunnel occupied by the fish is 39 cm long and 15 cm in diameter. The rear portion of the tunnel is covered with a removal cap of fine mesh (1-mm) screen. Water velocity is controlled by a rheostat on the motor. Water temperature ranged from 21-23 °C in all trials for all species.

During testing, three components of swimming performance and recovery were evaluated:

- Rheotaxis – head-first orientation into the direction of water flow.
- Endurance – or "time-to-fatigue;" the length of time that a fish was able to maintain its position in flowing water.
- Station-holding behavior – method used by the fish to maintain its position in flowing water.

Fish were placed in the working section of the swim tunnel and allowed to habituate 15-30 min in low flow (5-10 cm/s). At the end of the habituation period, water velocity was increased over a 2- to 3-sec interval to the test velocity and a stopwatch started to begin timing. Test velocities ranged from 30 to 90 cm/s. If the fish failed to exhibit rheotaxis, it was allowed a 1- to 2-min rest before flow was again increased to the test velocity. If after multiple attempts, it still did not exhibit rheotaxis, it was considered a non-swimmer and excluded from further testing and subsequent analysis.

When a fish oriented into the flow, the test was continued for 200 min or until the fish could no longer maintain station. During the trial, swimming behaviors of the sturgeon were identified and the duration of each behavior was timed separately (when trials were of long duration and individual behaviors were prolonged) or estimated following the trial (when trials were of short duration and/or individual behaviors were intermittent). Any fish that could no longer maintain position, and was swept back becoming impinged on the screen, was gently stimulated by fanning water against the screen using a broad wooden probe. If the fish was unable to dislodge itself from the screen, the test was ended and time noted.

At the conclusion of each trial, water temperature was measured to the nearest 0.5 °C with a mercury-filled thermometer. The fish was removed from the tunnel and placed in a plastic bag or an enamel pan of water. For sturgeons, total length (TL) and fork length (FL) were measured to the nearest millimeter by allowing the fish to relax adjacent to a ruler and measuring the distance from the tip of its snout to the tip of its caudal fin and to the innermost curve of the caudal fin, respectively. For live paddlefish, measurement of TL is problematic because the upper lobe of the heterocercal tail does not relax along the longitudinal axis of the fish's body. Consequently, paddlefish were measured from tip of rostrum to eye (rostrum length, RL), and from eye to innermost curve of tail (eye-to-fork-length, EFL), and the combined measurement (RL+EFL) was used to approximate total length for each fish. Based on morphometric data for a preserved series of similarly sized paddlefish, the authors believe that this measurement underestimates true TL by less than 10 percent (mean underestimation of true TL = 8 percent, range underestimation 2-11 percent, N=30, unpublished data). Tested fish were placed in holding tanks (separate from those housing untested fish) and observed for any injuries, mortality, or changes in behavior.

A total of 177 fish ranging in size from 62-200 mm TL were tested (Table 2). All fish tested showed no signs of physical impairment either during or after testing. No injuries were sustained and no mortality observed as a result of experiments. There were no apparent changes in behavior following tests. Many fish were healthy 1-2 years after testing.

Table 2
Number (N) and Sizes (TL) of Fishes Tested

Species	**N**	**Mean Size (mm)**	**Size Range (mm)**
Paddlefish	42	89.8	62-124
Lake sturgeon	44	169.0	130-200
Pallid sturgeon, >115 mm TL	48	133.7	116-159
Pallid sturgeon, ≤115 mm TL	43	91.3	74-115

ANALYTICAL METHODOLOGY: Rheotaxis was described as the percentage of fish tested at specific water velocities that successfully oriented into the flowing water. Because not all species were tested at all water velocities, ranges of water velocities were used so that species could be compared.

Swimming speeds of fish were classified by endurance predicted for a given water velocity as sustained, prolonged, or burst (Table 3). An additional category is referred to as "escape speeds," defined as the velocity at which predicted endurance was 1 min or less, i.e., the upper limits of prolonged swimming and the entire range of burst swimming. Defining minimum "escape speed" in this matter provides a more environmentally conservative estimate of entrainment risk by considering lower water velocities. It is also biologically meaningful, since changes in swimming performance parameters other than endurance (i.e., rheotaxis, swimming behavior) may take place at velocities lower than burst speeds.

Table 3
Swimming Speeds of Fishes (Adams et al. 1999)

Type	Definition	Endurance
Sustained	Depends on aerobic metabolism; does not result in muscular fatigue; used in migrations, foraging, routine activities.	>200 min
Prolonged	Utilizes both aerobic and anaerobic metabolism; results in fatigue.	30 sec to 200 min
Burst	Depends on anaerobic metabolism; quickly depletes short-term energy reserves; used in prey capture, predator avoidance.	<30 sec

Endurance at prolonged and burst swimming speeds typically decreases with increased water velocity and can be described (and predicted) using statistical models. The relationship between the two variables may be linear (if there is a continuous, constant transition from prolonged to burst speed), curvilinear (if rate of decrease slows at higher speeds), or disjunct (if there is an abrupt reduction in endurance from the upper limit of prolonged swim speeds to the lower limit of burst speeds). Previous studies of swimming performance of small fishes (<200 mm TL) indicate that most relationships are linear or curvilinear (e.g., Adams et al. 1999, 2000; Hoover and Killgore 2002).

Predictive models of swimming endurance were developed in SAS language using regression analysis with water velocity as the independent (predictor) variable and endurance as the dependent (response) variable (Hatcher and Stepanski (1994). Fish exhibiting sustained swimming and those that were non-swimmers were excluded from model development. Curvilinear and linear models were developed simultaneously. The model with greatest predictive ability was used to represent data for that species.

Swimming and station-holding behaviors were categorized and quantified. Classification of behavior was based on previous studies (Adams et al. 1997, Adams et al. 1999) and on novel observations in this study. Duration of each behavior was estimated following each trial and mean time for each velocity was calculated.

RHEOTAXIS: A majority of individuals in all species were rheotactic, but degree of rheotaxis varied among species and water velocities (Figure 1). More than 90 percent of paddlefish overall and in any range of water velocity oriented into the current. Approximately 80 percent of sturgeon oriented into the current overall, but rheotaxis of small pallid sturgeon steadily declined at higher velocities to a low of 50 percent at 65-75 cm/s. Small pallid sturgeon could not swim beyond this speed. Lake and large pallid sturgeon, however, exhibited a bimodal distribution in rheotactic behavior. Rheotaxis declined (68-74 percent) at moderate velocities, but increased again (>80 percent) at the highest velocities tested.

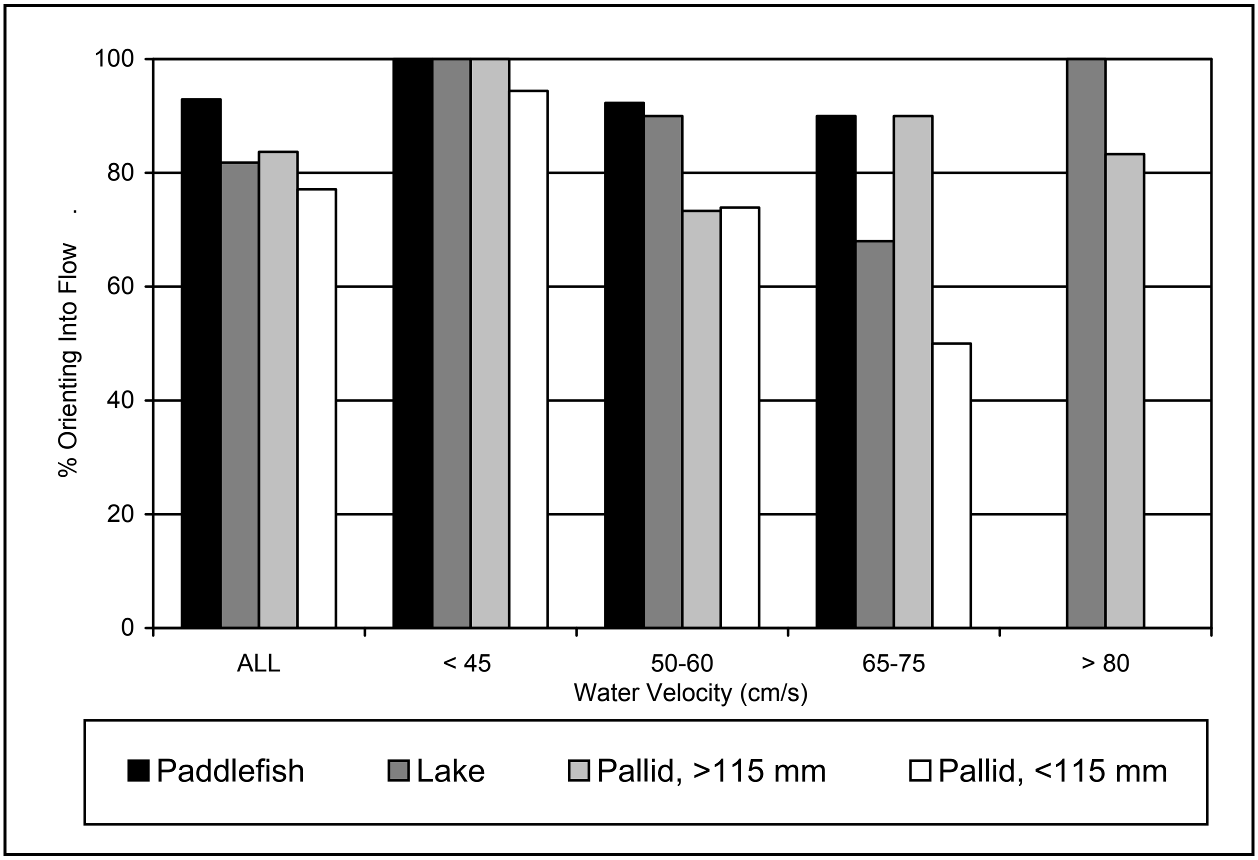

Figure 1. Rheotaxis among paddlefish and sturgeons

SWIMMING ENDURANCE AND ESCAPE SPEED: Sustained swimming (>200 min) was observed in all species. Maximum sustained swimming speeds were: paddlefish, 40 cm/s; lake sturgeon, 30 cm/s; large pallid sturgeon, 35 cm/s; small pallid sturgeon, 20 cm/s. Although paddlefish were the smallest of all groups tested, they exhibited the highest sustained swimming speeds, which is consistent with their "cruiser" morphology and behavior.

Significant regression models relating endurance to water velocity were developed. These explained 36 to 63 percent of the variation between the variables for each of the species (Table 4). R^2 values were comparable to or somewhat lower than those for swimming endurance models of other fishes, including juveniles of a northern population of pallid sturgeon ($R^2 >$ 0.80), two size classes of a midwestern shiner ($R^2 = 0.39$ and $R^2 = 0.68$), and juvenile bowfin (R^2=0.74), all of which were handled in the same manner and tested in the same apparatus as the fishes in this study (Adams et al. 1999, 2000; Hoover and Killgore 2002). Those fish, however, were all fasted 48 hr and tested in post-absorptive condition, which minimizes influence of recent meals and nutritional state and reduces variability among individuals. It is standard protocol for fish physiologists but is not as representative of the responses of naturally feeding fishes.

Models developed herein can be used to establish ranges of prolonged swimming speeds: i.e., minimum velocity tested at which sustained swimming did not occur at a velocity corresponding to a predicted endurance of 30 sec. Ranges of prolonged swimming speeds for the four groups of fish tested were: paddlefish, 30-57 cm/s; lake sturgeon, 45-75 cm/s; large pallid sturgeon, 40-54 cm/s; and small pallid sturgeon, 35-57 cm/s. Models can also be used to establish ranges of burst speeds: velocity corresponding to 30 sec endurance to maximum velocity at which swimming was observed. Burst speeds were: paddlefish, 57-75 cm/s; lake sturgeon, 75-85 cm/s; large pallid sturgeon, 54-90 cm/s; small pallid sturgeon, 57-70 cm/s. These results indicate that variability in swimming speeds decreases at higher velocities when anaerobic processes become the controlling factor.

Table 4
Swimming Endurance Models

Species	Model	R^2	P
Paddlefish	Log_{10}(Endurance) = 1.693-0.035[Velocity]	0.49	0.0001
Lake sturgeon	Log_{10} (Endurance) = 2.537-0.038[Velocity]	0.36	0.0020
Pallid sturgeon >115 mm	Log_{10} (Endurance) = 12.264–0.341[Velocity] + 0.002[Velocity2]	0.63	0.0001
Pallid sturgeon <115 mm	Log_{10} (Endurance) = 3.052-0.059[Velocity]	0.37	0.0001

At velocities < 55 cm/s, pallid sturgeon exhibited greater endurance than paddlefish (Figure 2). At velocities of 55-75 cm/s, paddlefish exhibited greater endurance than pallid sturgeon. Lake sturgeon, however, at 45-85 cm/s exhibited the greatest endurance of the four groups of fishes tested. Some interspecific variation can be attributed to morphological differences. Lake sturgeon, because of their short, muscular peduncle, are better able to generate thrust than pallid sturgeon. Some interspecific variation, though, may be directly attributable to size. Swimming endurance within a species is directly related to body mass (Peake et al. 1997; Adams et al. 1999, 2000). Differences in endurance between the large and small pallid sturgeon are pronounced especially at 40 cm/s, at which large pallid sturgeon had greater endurance, and 60-70 cm/s, at which smaller pallid sturgeon had greater endurance (Figure 2). Most of the paddlefish tested were smaller than the smallest pallid sturgeon.

Although ranges of sustained, prolonged, and burst speeds were substantially different among the four groups of fishes, minimum escape speeds were very similar for three of the groups tested (Figure 2). Minimum escape speeds for paddlefish, large pallid sturgeon, and small pallid sturgeon ranged from 48.4 to 51.7 cm/s. Escape speeds for lake sturgeon were substantially higher: 66.8 cm/s.

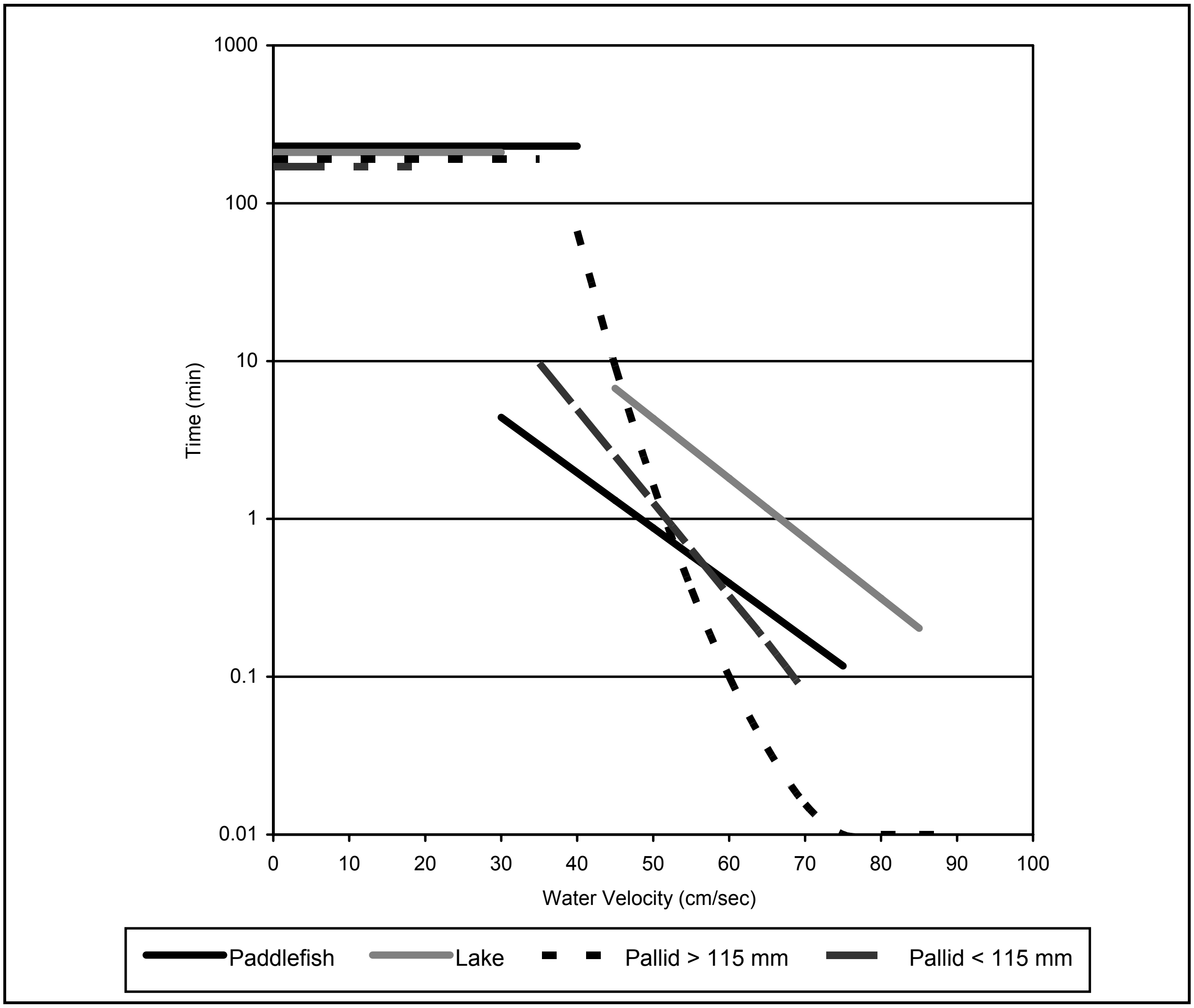

Figure 2. Swimming endurance models for paddlefish and sturgeons

SWIMMING BEHAVIOR: Six swimming behaviors were observed (Table 5). One of these, free-swimming, represented open-water swimming, moving forward against current, in a manner typical of most pelagic fishes. The other five behaviors were variations of substrate-based station-holding, static resistance against current, typical of many benthic fishes.

Paddlefish, like sharks, swim continuously, and were not observed in contact with the bottom of the swim tunnel (except when feeding on sunken food). Skimming and hunkering were frequently observed in all species of sturgeons. Creeping, tail-bracing, and wedging were infrequently observed, and only in pallid sturgeon.

Lake sturgeon and large pallid sturgeon free-swam approximately 50 percent of the time during swimming performance trials, small pallid sturgeon less than 20 percent of the time (Figure 3). Time spent free-swimming was comparatively low at water velocities up to 60 cm/s, and high at water velocities from 65 to 85 cm/s. At higher water velocities, benthic station-holding behaviors were less effective in maintaining position and avoiding contact with the back screen.

Table 5
Swimming Behaviors of Acipenserform Fishes

Behavior	Definition
Free-swimming	Fish holds station in mid-water by continuously and vigorously undulating its body and moving its tail from side to side
Skimming	Fish holds station with its ventral surface on or just above bottom, gently undulating its body and moving its tail from side to side
Hunkering	(Also called "substrate appression.") Fish holds station with its ventral surface on bottom, body straight, with no undulation of body or movement of tail; rostrum is angled downward, dorsal surface is arched upward, and pectoral fins are turned up in back; conserves energy
Creeping	Fish holds station with its ventral surface on bottom and periodically rotates its pectoral fins and drags body forward to account for slippage backward
Tail-bracing	Fish holds station with ventral surface on bottom and presses caudal fin against back of tank
Wedging	Fish holds station with ventral surface on or near bottom, rostrum inserted tightly into crevice under front screen, hunkering or skimming

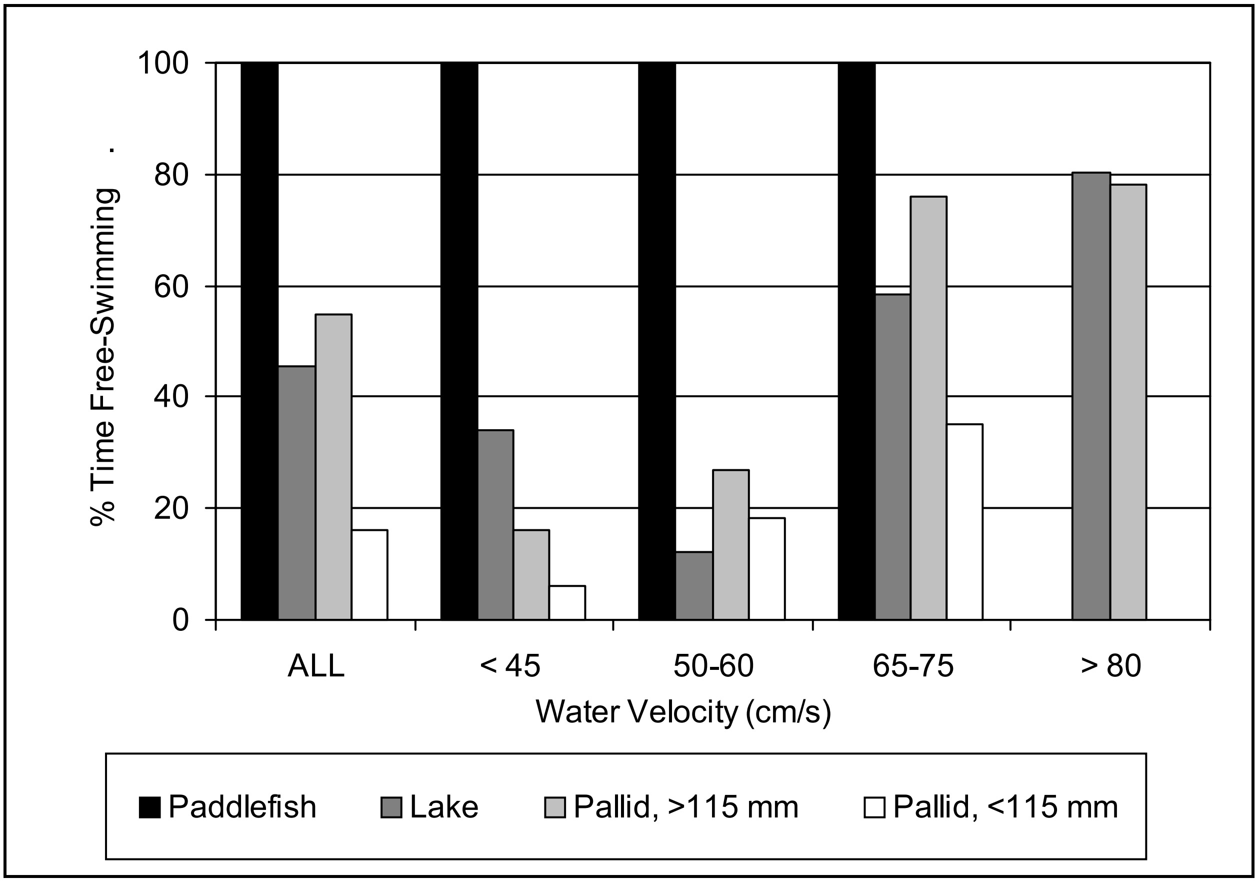

Figure 3. Mean time spent free-swimming by paddlefish and sturgeons

ASSESSMENT OF RISKS: Intake water velocity data are available for simulations of flow fields created by hydraulic dredges (http://el.erdc.usace.army.mil/dots/doer/flowfields/dtb350.html). For any given point within a flow field, a simple assessment of entrainment risk presented by that water velocity can be determined based on swimming performance data for a tested fish species (Figure 4). Components of swimming performance represent three separate and distinct swimming responses that cumulatively dictate entrainment risk at any given water velocity. Data on rheotaxis provide an estimate of fish likely to be entrained due to failure to orient into current (i.e., percent of non-swimmers). Values for escape speeds (or burst speeds) indicate whether a species is physiologically capable of resisting that flow (i.e., disparity of escape speed versus suction velocity). Data on swimming behavior indicate whether or not a fish's mode of locomotion, or station-holding, is likely to increase probability of entrainment (i.e., from high-risk, bottom-hugging behaviors).

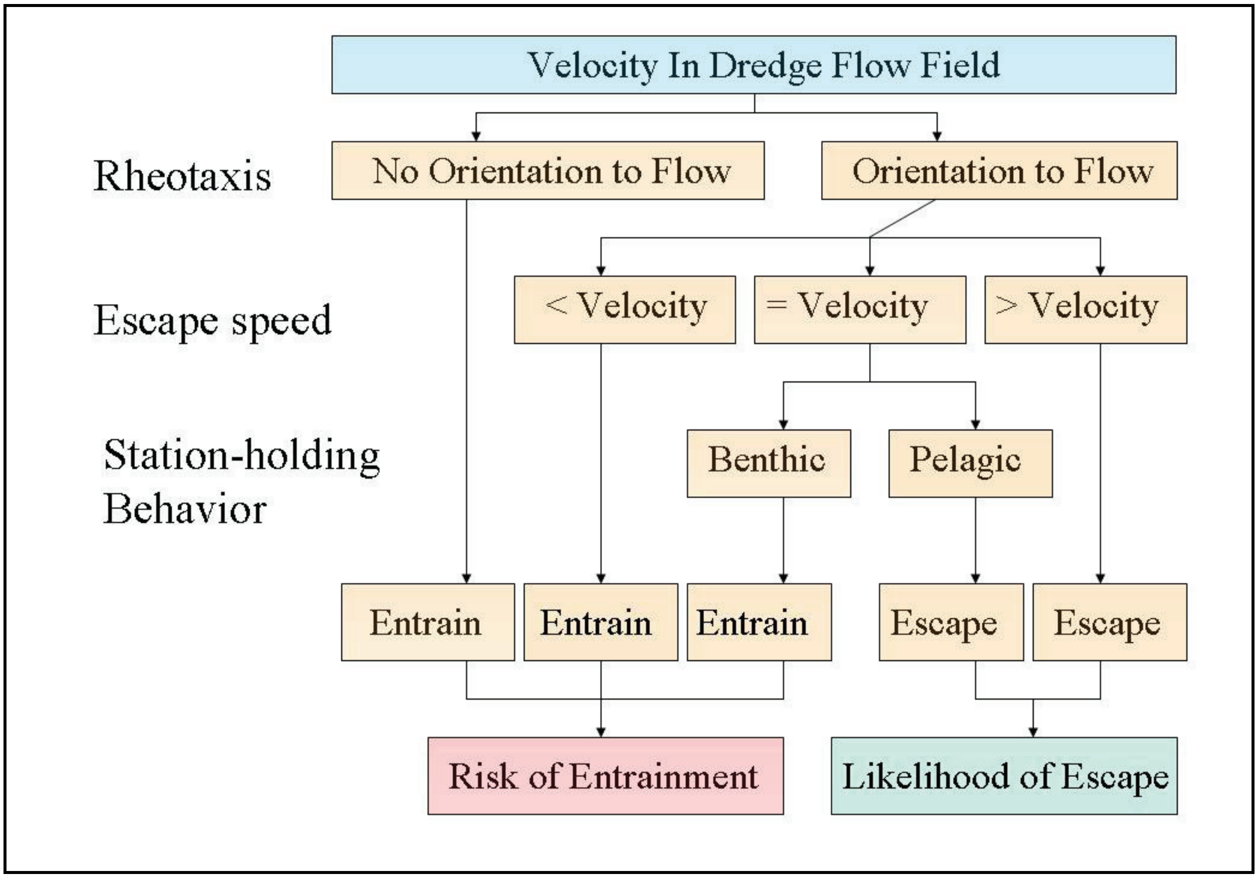

Figure 4. Conceptual model for assessing risk of entrainment by dredge based on swimming performance of fishes

For example, a cutterhead dredge drawing 15 or 20 ft/sec, can create suction velocities of 50 cm/s up to 1.5 m from the dredge intake (http://el.erdc.usace.army.mil/dots/doer/flowfields/dtb350.html). Relative risk of entrainment for the four groups of fishes tested in this study can be readily evaluated at this velocity qualitatively from their swimming performance data. Paddlefish are strongly rheotactic and very unlikely to be entrained because of failure to orient against a flow field (<10 percent of fish tested were non-swimmers); their escape speed is approximately 50 cm/s, but because they are pelagic free-swimmers, and not stationary on the bottom, risk of entrainment is low. Lake sturgeon, also strongly rheotactic, are benthic station-holders, but have a high escape speed and are also unlikely to be entrained. Pallid sturgeon, however, frequently fail to exhibit rheotaxis (>25 percent of fish tested were non-swimmers) and those fish would be likely to be entrained; like lake sturgeon, they are benthic station-holders, but unlike lake sturgeon, their escape speeds are low, placing them at higher risk of entrainment.

Table 6
Evaluating Risk of Entrainment at 50 cm/s

Species	Rheotaxis: % Non-swimmers	Escape Speed: Minimum, cm/s	Swimming Behavior: % Time Benthic	Risk
Paddlefish	7.7	48.4	0	Lowest
Lake sturgeon	9.1	66.8	87.7	Low
Pallid sturgeon >115 mm	26.7	51.5	73.2	High
Pallid sturgeon ≤115 mm	26.1	51.7	81.8	Highest

With larger data sets, risk assessments could also be evaluated quantitatively, resulting in values ranging from 0.00 (no risk of entrainment) to 1.00 (no chance of escape). Such a value could be calculated as a simple sum: the percentage of sturgeon that do not exhibit rheotaxis when experiencing an increase in water velocity (i.e., non-swimmers) plus the percentage of sturgeon that exhibit rheotaxis but cannot escape that intake water velocity. For sturgeon with an escape speed significantly lower than a given water velocity, all remaining fish are presumed lost to entrainment (Risk = 1.00). For sturgeon with an escape speed equal to water velocity, the percentage of swimming fish lost to entrainment will be lower, equal to those employing station-holding techniques other than free-swimming (Risk = 100 - % of free-swimming sturgeon). For sturgeon with an escape speed substantially greater than water velocity, the percentage of swimming fish lost to entrainment will be zero (Risk = % non-swimming fish only). Risk is presumed to be zero when intake water velocities approximate speeds at which fish exhibit sustained swimming (>200 min) or prolonged swimming (1-200 min).

These estimates of risk are not tools for predicting "take" under the Endangered Species Act. They do not address effects of confounding physical variables associated with dredging (e.g., noise, turbidity, temperature, substrate) or biological variables associated with sturgeon populations (e.g., population size, density, distribution, habitat preferences). Rather, they reflect the probabilities of an individual fish being entrained by a specific water velocity. Risk estimates can be used to identify species and size classes of sturgeon potentially susceptible to entrainment by various types and sizes of dredges. They can provide support for redefining dredging windows and for selecting lower-risk dredging alternatives. This approach assumes that risk of entrainment is determined principally by water velocities produced by a dredge and by the resulting sequence of swimming responses to those velocities by the sturgeon.

Total risk of entrainment, however, is a cumulative value associated with behavioral, physiological, and demographic data. In addition to swimming performance data, a risk analysis would require information on responses of sturgeon to dredge-induced perturbations like noise and turbidity, and localized sturgeon abundance and distribution at the dredging location. Continued behavioral studies under the DOER Program, along with increased monitoring of sturgeon populations, will improve predictions of risk associated with dredge entrainment.

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