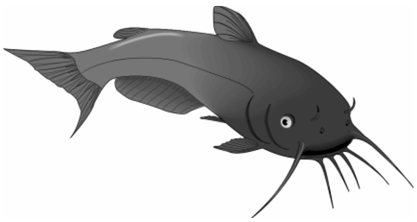
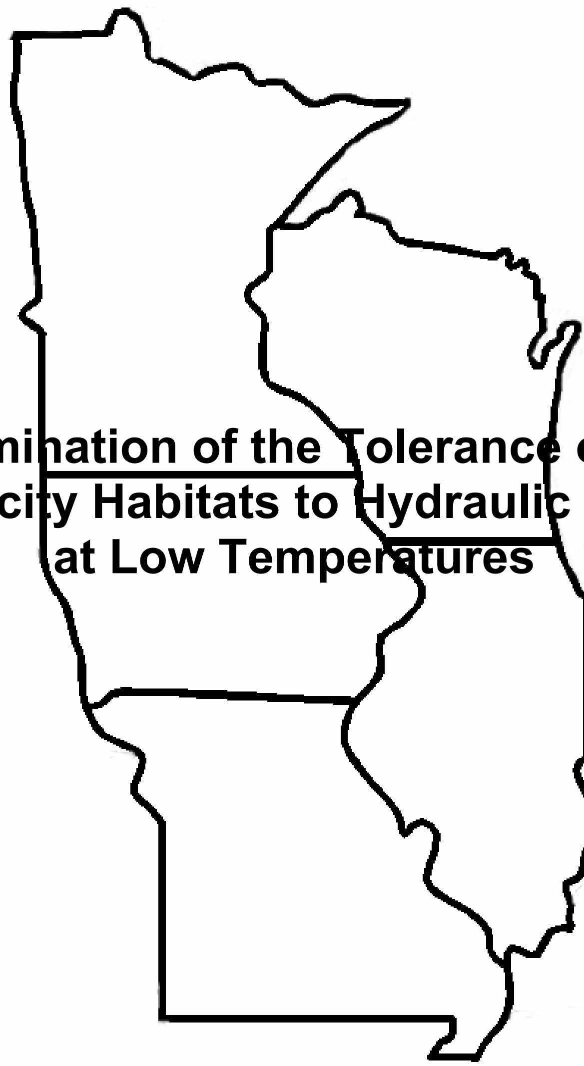
ENV Report 33

Interim Report For The Upper Mississippi River – Illinois Waterway System Navigation Study





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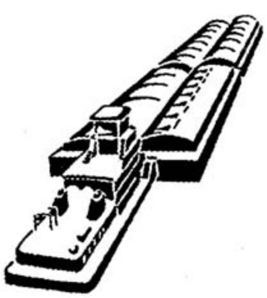

June 2004

US Army Corps of Engineers

Rock Island District
St. Louis District
St. Paul District

Upper Mississippi River - Illinois Waterway System Navigation Study

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Determination of the Tolerance of Fish in Low-Velocity Habitats to Hydraulic Disturbance at Low Temperatures

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Interim report

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ABSTRACT: Upstream-bound vessels in the Upper Mississippi River-Illinois Waterway and other river systems may displace overwintering fish residing behind wing dams. Displacement flow rates were determined for young-of-the-year bluegill (*Lepomis macrochirus*) and channel catfish (*Ictalurus punctatus*) at 1, 2, and 4 °C in a swimming-ability (swim) tunnel. The velocity change profile simulated that associated with barge passage, with an initial backflow, then an accelerating positive flow toward a predetermined peak flow velocity. Proportion of fish displaced, time to displacement, and displacement flow rate were quantified for each trial. In addition, a sand wave typical of the main channel of a large river was simulated in a flume. Both fish use of the sand wave and displacement were quantified with varying flow and temperatures. As temperatures declined in the swim tunnel experimental trials, displacement typically occurred for both species before peak velocities were reached. Apparently, exhaustion was not the primary mechanism causing displacement. Acceleration of flow as a vessel passes is an important factor. Swimming ability of both species was similar at low temperatures, which counters earlier work demonstrating that channel catfish outperform bluegill at cold temperatures. In the sand wave experiment, both species were typically displaced from sand wave depressions at greater than 0.1 m/s. A low flow eddy was created at the upstream end of the depression, potentially providing flow refuge if a fish remained stationary within the eddy.

Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River – Illinois Waterway (UMR – IWW) System Navigation Study. The information generated for this interim report will be considered as part of the plan formulation process for the System Navigation Study.

The UMR – IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul, under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing and, in consideration of existing system lock constraints, will result in traffic delays that will continue to grow in the future. The System Navigation Study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic and to consider ecosystem restoration needs related to the navigation system. The study will determine the location and appropriate sequencing of potential navigation and improvements and ecosystem restoration measures in the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report, which is the decision document for processing to Congress.

This report was written by Messrs. Robert J. Sheehan, Paul S. Wills, Michael A. Schmidt, and Joseph E. Hennessy, Cooperative Fisheries Research Laboratory, Southern Illinois University, Carbondale, IL.

1 Introduction

The approach for this study was based on the outcome of the Navigation Impacts investigations (Sheehan et al. 2004) and preliminary effects of vessel passages in the vicinity of wing dams, conducted at the U.S. Army Corps of Engineers (USACE) Hydraulics Laboratory, Waterways Experiment Station (WES), in Vicksburg, MS, in April 1997 under the direction of Dr. Steve Maynord of the Navigation Effects Group. The preliminary trials at the Hydraulics Laboratory focused on vessel-induced velocity changes in the vicinity of wing dams because these navigation structures provide slack water microhabitats (downstream of and in the scour hole at the tip of wing dams) in which fish winter (Sheehan et al. 2004). The movements of injected dye and plastic beads (density 1.07 g/mL) placed in wing dam slack water microhabitats were observed during vessel passages to assess the magnitude and direction of velocity changes during vessel passages.

This study was originally conceived to determine the minimum distance from a particular low-velocity habitat that the average upstream- and downstream-bound commercial vessel must travel to cause hydraulic displacement of wintering fish from their microhabitats. However, the preliminary vessel passage trials conducted at the Hydraulics Laboratory showed that downstream-bound vessels have little influence on water velocities downstream of and in the scour hole of the wing dam.

In contrast, upstream-bound vessel trials showed substantial effects on velocities downstream of the wing dam and in the scour hole. The bow wave (positive vessel displacement wave) of upstream-bound vessels slightly increased velocities downstream of the wing dam, and the velocity vector was directed primarily towards shore. Velocities in the scour hole appeared to increase in a downstream direction due to the bow wave as the vessel approached. Forces exerted by the bow wave downstream of the wing dam appeared to be in opposition to eddy forces generated by the wing dam, resulting in the bow wave being somewhat canceled out. The return wave associated with the upstream vessel passage, however, led to substantial increases in velocity downstream of the wing dam and in the scour hole, such that some of the dye and plastic beads placed in these microhabitats was subsequently displaced into the navigation channel. These displacement effects were greatest near the wing dam tip and diminished towards shore. Preliminary assessment of these findings suggests that the return wave contributes to the water movements caused by the eddy behind the wing dam.

It should be noted that beads placed on the bottom in the model navigation channel were not displaced downstream by the flowing water, whereas beads placed on the bottom behind the wing dam were displaced subsequent to the upstream-bound vessel passages. The lack of displacement of the beads in the navigation channel is consistent with the vertical decline in velocity from the surface to the bottom, caused by the hydrodynamic drag of the channel bottom. A possible explanation for the displacement of beads placed on the bottom downstream of the wing dam is that return waves typically exhibit uniform velocities from surface to bottom. It should also be noted that particles (such as fish) downstream of wing dams, whether suspended on or near the bottom, will be at similar risk of being displaced into the river channel.

The preliminary vessel-passage trials indicated the possibility that fish wintering in scour holes or downstream of wing dams will be displaced into the channel subsequent to upstream-bound vessel passages. Findings indicate mortality at temperatures less than 4 °C in young-of-the-year (YOY) channel catfish and bluegill is increased with increased frequency of displacement from slack water microhabitats (Sheehan et al. 2004).

Given these circumstances, the goal of this study is to determine how water velocity changes will affect fish overwintering in slack water microhabitats. To achieve this goal, measurements were made of the magnitude of velocities which cause displacement of fish from low-velocity habitats, such as downstream of wing dams and within scour holes. Also studied was the magnitude of velocity increases over sand waves that cause displacement of fish from downstream low-velocity sand wave troughs, a habitat reportedly used by fish during winter.

Distance from the sailing line affects the magnitude of velocity changes generated by the average upstream-bound vessel in slack water microhabitats. Measurements of velocities that will cause displacement of fish can be used to determine how much of the slack water behind wing dams will be affected by vessel passages at different distances from the wing dam. This information can also be used to estimate relationships between sailing line distance from scour holes and displacement of fish from scour holes.

2 Materials and Methods

Test Fish

YOY channel catfish and bluegill obtained from Logan Hollow Fish Farm, Gorham, IL, were used in the study. The fish were initially held in a water-reuse raceway system at temperatures ranging from 23 to 27 °C and fed a maintenance diet of Silvercup Floating Trout Feed. Test fish were then acclimated to study conditions in two, 1.8-m-diam circular tempering tanks with an 8:16 light:dark cycle to simulate winter photic conditions. Each species was held and tempered separately. Temperature was reduced at a rate of 2 °C/day until 7 or 8 °C was reached; thereafter, temperature was reduced 1 °C/day until the desired test temperature was reached. Fish were held for a minimum of 1 day at each test temperature before experiments began.

Wing Dam Simulations

The wing dam simulations were conducted in a climate-controlled, insulated, refrigerated room to ensure regulation of water temperature throughout the experiments. A swimming-ability tunnel (swim tunnel) was used to measure median displacement velocities (DV50s) for YOY bluegill and channel catfish at 1, 2, and 4 °C. The swim tunnel used consisted of a loop of 25-cm-diam polyvinyl chloride (PVC) pipe through which water was circulated (Figure 1). Water was moved through the system by a propeller driven by a 1.5-hp variable speed motor. Flow was measured digitally and monitored throughout each test with a propeller-type flow meter. A plastic mesh screen placed 1 m apart at each end of the swim tunnel defined the boundaries of the test area. The downstream screen was electrified with a wire grid charged by a “Harvard Stimulator” set to deliver an electric shock of 25 V DC for 30 milliseconds each second. This combination of voltage, pulse frequency, and duration was chosen because it stimulated test fish to avoid the downstream screen without causing apparent harm.

A range-finding test was conducted at each temperature to determine the maximum velocity that each species could be expected to withstand. Based on the results of these tests, a range of between four and seven peak velocities, including 0 m/s as a control, was chosen for the definitive test trials.

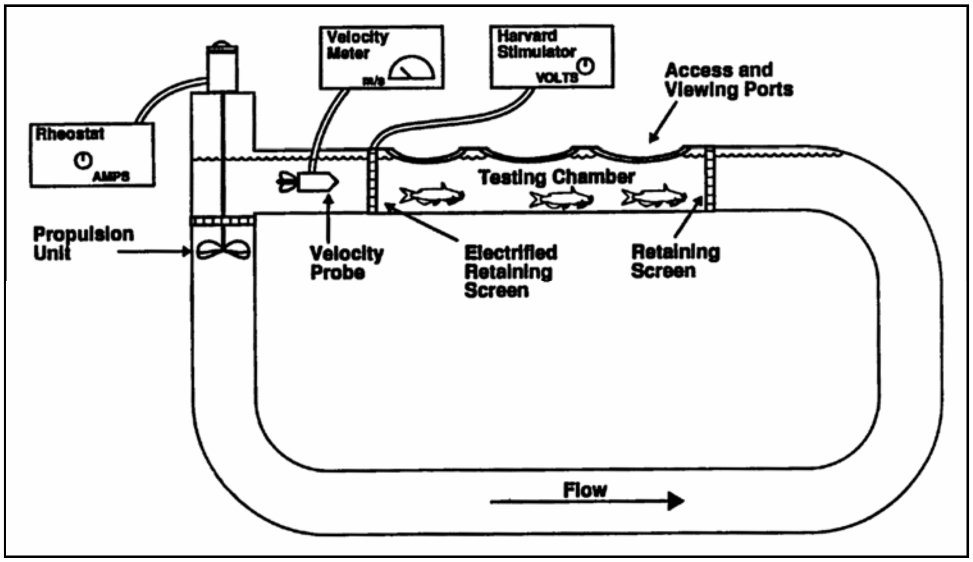

Figure 1. Schematic diagram of swim tunnel used to measure median DV50s for YOY bluegill and channel catfish at 1, 2, and 4 °C

Fish were tested in the swim tunnel individually. To simulate the velocity change profile associated with barge passage, each trial began with an induced “backflow” having a peak mean velocity of -0.04 m/s (SD = 0.01) and lasting approximately 5 sec. Positive flow (in the direction opposite the backflow) was then increased linearly for 50 sec to the peak velocity, and then decreased linearly for 50 sec back to 0 m/s. A fish was considered displaced if it was pinned to the electrified grid for a minimum of 5 sec at any time during the 105-sec duration of a trial. Ten replicates were conducted for each peak velocity. Peak velocity exposures were randomized over time within a test temperature to counterbalance time effects.

Probit analysis (Finney 1971) was used to analyze the data at each test temperature and for each species. The criteria used to determine a valid DV50 were as follows:

a. A Pearson’s Chi-square goodness-of-fit test to determine if the data reasonably fit the probit model.

b. At least one velocity where ≥20 percent and ≤50 percent of fish are displaced.

c. At least one velocity where ≥50 percent and ≤80 percent of fish are displaced.

Sand Wave Simulations

To simulate a sand wave typical of the main channel of a large river, a 2-m-long flume was constructed that incorporated a simulated sand wave (Figure 2).

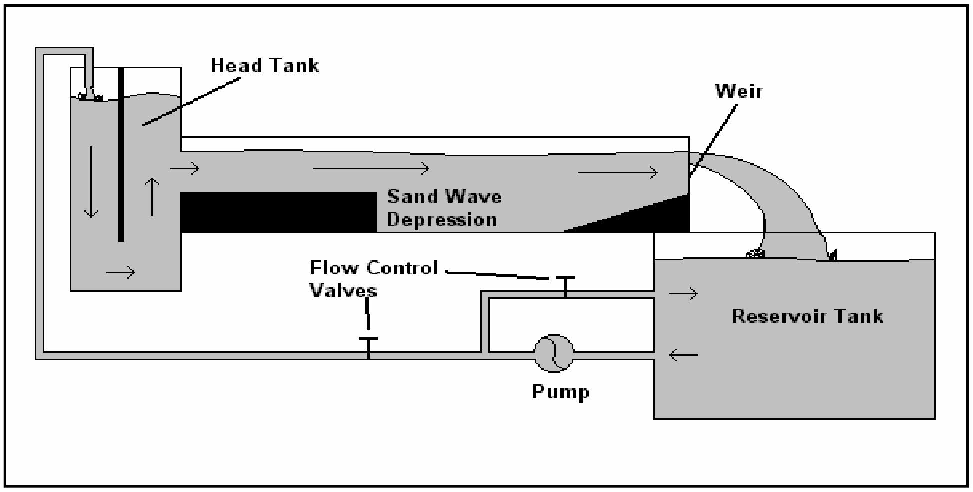

Figure 2. Cross-sectional schematic diagram (not to scale) of the simulated sand wave flume used to determine the magnitude of velocity increases over sand waves that cause displacement of fish from downstream low-velocity sand wave troughs

The flume was a 15-cm-wide, 1-m-long channel which widened to 30 cm for 50 cm at its downstream end. The 1-m channel portion contained the simulated sand wave depression and defined the boundaries for simulation tests. Water depth at the upstream 0.5 m of the flume, prior to the simulated sand wave, was 13 cm. The sand wave was simulated by constructing a 13-cm step within the flume. Water depth at the bottom of the step was 26 cm. At 0.5 m downstream from the step, the bottom was sloped up to gradually bring the water depth back to 13 cm. An adjustable weir was used at the distal end of the flume, where the water exited, to maintain a constant water depth along the length of the flume regardless of water velocity. Water exiting the flume flowed into a 1.2-m-diam, 1.2-m-deep reservoir tank. Water was pumped with two 1.5-hp centrifugal pumps into a 90-L rectangular head tank that was baffled to reduce the turbulence of water entering the flume. Water flow in the head tank, and thus the flume, was regulated by four ball valves and monitored digitally with a propeller-type flow meter. The meter's sensor was placed immediately upstream of the simulated sand wave depression. Temperature was controlled in the system by four immersion-type 1.5-hp Minno-cool™ chilling units. Simulated sand wave (step) dimensions and expected flow patterns in and around the simulated sand waves were provided by WES. Flow patterns within the simulated sand wave were visualized at the full range of velocities encountered during testing using methylene blue as a tracer dye injected at various points within the water stream.

Trials were conducted to measure the maximum channel velocities that permitted fish to use the sand wave depression habitat at 1, 2, and 4 °C. Initially, four test fish were introduced to the system at a water velocity of 0 m/s; velocity was then increased at 3-min intervals by 0.05 m/s until 50 percent of the fish were displaced from the sand wave depression. Fish were considered displaced if they left the sand wave depression habitat (entering the channel flow) and failed to return for more than 15 sec. Five replicates were conducted for each species at each temperature. Time of displacement and displacement flow rate were recorded for each displaced fish.

A second set of trials was conducted during which a base flow of 0.10 m/s was established in the sand wave flume. Velocities in the flume were then increased from 0.10 m/s at 3-min intervals by 0.05 m/s until 50 percent of the fish were displaced from the sand wave depression. These simulations determined the mean increase in velocity, above 0.10 m/s, causing 50 percent displacement of fish at each of the test temperatures. Again, five replicates with four test fish in each replicate were conducted for each species at each temperature. Time of displacement and displacement flow rate were recorded for each displaced fish. Fish were considered displaced if they left the sand wave depression habitat (entering the channel flow) and failed to return for more than 15 sec.

3 Results and Discussion

Wing Dam Simulations

The DV50 determinations for channel catfish and bluegill showed general patterns of reduced tolerance to increases in velocity with decreasing temperature (Table 1). DV50s for bluegill, however, appeared to level off at and below 2 °C.

Table 1
DV50 Determinations at 1, 2, and 4 °C for Channel Catfish and Bluegill

Species	Temperature, °C	DV50, m/s	95% Fiducial Limit	p
Channel catfish	1	0.08	0.01-0.36	0.33
	2	0.18	0.11-0.23	0.28
	4	0.30	0.25-0.35	0.95
Bluegill	1	0.09	0.06-0.12	0.38
	2	0.09	0-0.17	0.11
	4	0.16	0.13-0.20	0.04

Note: DV50's are the peak velocity (m/s) of a velocity change profile, similar to that of a passing barge, necessary to displace 50% of fish from their position within a test chamber. DV50s determined using Probit analysis, p = probability of Pearson's chi-square test of goodness-of-fit (Finney 1971).

All but one of the DV50 determinations, bluegill at 2 °C, passed all three aforementioned criteria for consideration as a valid DV50. Although passing the second and third criteria, the bluegill at 2 °C failed to pass the Pearson chi-square test for goodness-of-fit to the probit model. An alternative chi-square test, the Likelihood Ratio chi-square goodness-of-fit test (Schlotzhauer 1991), however, did not indicate a substantial departure from the probit model ($p = 0.22$). Given that the 2 °C DV50 data did not appear to depart substantially from the probit model, and the other two criteria were satisfied, alternative models were not explored. The 95 percent fiducial limits for the DV50 of bluegill at 2 °C, however, were calculated using a student's t-value of 2.5705 rather than the t-value of 1.96 used for the others.

The DV50s for channel catfish were correlated with temperature to determine if it was tenable to estimate the 0 °C DV50 for this species via extrapolation. The linear regression was significant ($p < 0.05$). The line equation for the relationship was DV50 = 0.0722 × Temperature (°C) + 0.0157 (r^2 = 0.98). The estimated DV50 for channel catfish at 0 °C was 0.02 m/s, based on this relationship. The 0 °C DV50 for bluegill was estimated to be 0.09 m/s, because DV50s appeared to plateau at this value both at and below 2 °C for this species.

The majority of the fish displacements occurred prior to reaching the peak velocity (Table 2). Given the short duration of each test, most displacements were probably not due to tiring of the fish. Sheehan et al. (1990) found a sustained swimming stamina for channel catfish and bluegill of greater than 4 min at 0, 2, and 4 °C at a velocity of 0.1 m/s. Hence, the acceleration of water, rather than its velocity, may better explain the observed displacements. At low peak velocities the fish would experience very low acceleration of water and would more easily be able to compensate with small changes in swimming effort. However, at high peak velocities, acceleration would be greater, and the fish might not be capable of increasing swimming effort rapidly enough to compensate for the rapidly increasing force of the water. Data were converted for the DV50s (m/s) to median displacement acceleration rates (DA50s, m/s^2) (Table 3). An advantage to expressing the displacement event in terms of acceleration is that the prediction of peak displacement velocities should be possible for barge passage events that last for a shorter or longer period than the events simulated by these tests.

Table 2
Mean Percentage of Fish Displaced Prior to Reaching the Peak Velocity During DV50 Determinations

Species	Temperature, °C	% Displaced Prior to Peak Velocity	SD
Channel catfish	1	55.6	50.9
	2	84.4	18.5
	4	80.2	36.9
Bluegill	1	76.9	20.6
	2	65.1	25.1
	4	91.5	11.3

Table 3
DA50 Determinations at 1, 2, and 4 °C for Channel Catfish and Bluegill

Species	Temperature, °C	DA50, m/s^2	95% Fiducial Limit	p
Channel catfish	1	0.0015	0.0002-0.0073	0.33
	2	0.0036	0.0021-0.0046	0.28
	4	0.0060	0.0049-0.0071	0.95
Bluegill	1	0.0018	0.0012-0.0024	0.38
	2	0.0019	0-0.0035	0.11
	4	0.0033	0.0025-0.0040	0.04

Note: DA50s are the median acceleration rate of water (m/s^2) during a velocity change profile, similar to that of a passing barge, necessary to displace 50% of fish from their position within a test chamber. Acceleration rates were calculated from peak velocities used for DV50 determinations, and DA50s were determined using Probit analysis, p = probability of Pearson's chi-square test of goodness-of-fit (Finney 1971).

Based on the results from earlier studies (Sheehan et al. 2004), it is likely that the stamina of a fish, and thus its ability to fight future displacement, will depend on its displacement history.

Overall, the data clearly indicate that risk to hydraulic displacement, for fish wintering downstream of wing dams or similar structures, is inversely related to temperature. At low temperatures, channel catfish are stronger swimmers than bluegill (Sheehan et al. 1990), yet DV50s (and DA50s) were similar to bluegill at 1 °C, indicating similar tolerance to a velocity increase. This finding was not anticipated and may be explained by the behavior of the two species in the test system. Bluegill were inactive and they rested on the bottom, often on their sides, at the lowest test temperature. In contrast, channel catfish swam about at all temperatures, exposing themselves to water currents. These behaviors are consistent with observations for these two species at low temperatures in prior studies (Sheehan et al. 1990, 2004). The bluegill appeared to become somewhat anchored to the bottom at 1 °C. Also, by resting on their sides, only a small portion of their body cross-sectional area was exposed to the acceleration forces of the water. One or both of these factors probably accounted for the bluegill being able to resist velocity increases at 1 °C about as well as the channel catfish. Based on the factors aforementioned and the extrapolated DV50 value of 0.02 m/s for channel catfish, it is likely that at 0 °C bluegill are more capable of resisting a velocity change than channel catfish.

Sand Wave Simulations

In the first set of tests the fish swam about freely at all temperatures and did not use the sand wave depression habitat as velocities were increased. Because the fish never used the habitat, it was not possible to determine displacement under the experimental protocol. Due to this finding, the second portion of the work proposed was not necessary. A decision was made, however, to pursue these studies by asking the question in a slightly different manner. First, a base flow was provided in the simulation to promote use of the sand wave depression by the test fish. Then, water velocity was increased. The question became, What increase in channel velocity permits fish to use a sand wave depression at low temperature?

In this second set of tests, which used an initial base flow rate of 0.10 m/s, both bluegill and channel catfish tolerated only a slight increase in channel velocities before leaving the sand wave depression and becoming displaced (Table 4). At the lowest temperature tested, 1 °C, 50 percent of bluegill were not capable of staying within the sand wave even at the base channel velocity.

Observations of the tracer dye behind the simulated sand wave revealed a flow pattern that was consistent with what was expected based on data provided by the WES. An eddy (flowing against the main current) did extend 4.3 times the height of the step in the downstream direction at a channel velocity of 0.5 m/s, which is consistent with the information provided—that the eddy should extend approximately 4.6 times the height of the step in the downstream direction.

Table 4
Mean Change in Velocity (ΔV) Required to Displace 50 percent of Fish from a Simulated Sand Wave Habitat with a Base Channel Velocity of 0.10 m/s at 1, 2, and 4 °C (n = 5 trials with 4 fish per trial)

Species	Temperature, °C	Mean ΔV (m/s)	SD
Channel catfish	1	0.03	0.04
	2	0.01	0.02
	4	0.06	0.04
Bluegill	1	0.0	0
	2	0.03	0.02
	4	0.10	0.09

In addition, as indicated in the diagrams provided, a small eddy with a very low velocity current counter to the primary eddy occurred immediately downstream of the step. This small eddy acted as a sink for dyed water and quickly became apparent. This suggests that a neutrally or slightly negatively buoyant object (such as a fish) would have to expend very little energy if it “chose” to stay within the smaller, low-flow eddy at the upstream end of the simulated sand wave depression. The fish used in these tests, however, chose to leave the eddy and move into the current.

How applicable the results of the sand wave simulations are to real-world conditions is uncertain. Although it was possible to scale down the sand waves for laboratory evaluations, it is not possible to scale down the test animals. Also, it is not known whether YOY fish utilize sand waves in the river for wintering to any extent. Adult fish, with their larger size and greater physiological scopes of activity at low temperatures, may find sand waves to be more hospitable than the tested YOY specimens. Larval channel catfish have been observed in sand wave depressions during the winter (Sheehan et al. 2004); however, based on observations, YOY bluegill and channel catfish may not winter in sand wave depressions.

References

Finney, D. J. (1971). *Statistical methods in biological assay*. Griffin Press, London, England.

Schlotzhauer, D. C. (1991). "Computing goodness-of-fit chi-square statistics with SAS software," *Observations: The Technical Journal for SAS Software Users* 1(1), 17.

Sheehan, R. J., Bodensteiner, L. R., Lewis, W. M., Logsdon, D. E., and Scherck, S. D. (1990). Long-term survival and swimming performance of young-of-the-year river fishes at low temperatures: Links between physiological capacity and winter habitat requirements." *The restoration of Midwestern Stream habitat.* 52nd Midwest Fish and Wildlife Conference Proceedings of Symposium, Rivers and Streams Technical Committee, North Central Division of the American Fisheries Society, 4-5 December 1990, Minneapolis, MN, R. Saur, ed., 98-108.

Sheehan, R. J., Wills, P. S., Schmidt, M. A., and Hennessy, J. E. (2004). "Determinations of the fate of fish displaced from low-velocity habitats at low temperatures," ENV Report 32, Cooperative Fisheries Research Laboratory, Southern Illinois University, Carbondale, IL, for U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul.