ILLINOIS NATURAL HISTORY SURVEY

Potential impact of steel-hulled barges on movement of fish across an electric barrier to prevent the entry of invasive carp into Lake Michigan

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Center for Aquatic Ecology

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Background

Harmful invasive fishes have a long history of negative impacts on important sport and commercial fishes in the United States. Two of the largest drainage basins in North America are particularly vulnerable to the potential effects of invasive fishes: the Laurentian Great Lakes, where several sport fish populations have been compromised at least in part by exotic fishes, and the Mississippi River drainage basin, where exotic species may become established directly through shipping activities and accidental aquaculture releases (Mills et al. 1993) or indirectly through communication with the Great Lakes drainage basin via the man-made Chicago Sanitary and Ship Canal (Canal). In fact, man-made canals have a long history of allowing unwelcome invaders into the Great Lakes, with extensive negative consequences for ecologically and economically important fishes.

The man-made Chicago Sanitary and Ship Canal has become a gateway for the transfer of invasive, aquatic species between two of the largest drainage basins in North America: the Mississippi and the Great Lakes-St. Lawrence (Kolar and Lodge 2002). Nuisance organisms that have moved through the canal from Lake Michigan to the Mississippi drainage in the past decade include the zebra mussel *Dreissena polymorpha*, the white perch *Morone americana* and the round goby *Neogobius melanostomus*. The zebra mussel overgrows and fouls native mollusks and is associated with declining and endangered populations of native mussels in the Upper Mississippi River. The zebra mussel also causes economic damage by plugging water intakes and fouling boat hulls. The white perch is currently hybridizing with the native white bass *Morone chrysops* and yellow bass *Morone mississippiensis*, leading to concerns about genetic introgression (M. Pegg, J. Epifanio, Illinois Natural History Survey, personal communication). The round goby competes with native bottom-dwelling fishes, locally extirpating native species such as sculpins (Janssen and Jude 2001), and consumes the eggs of native species, including sport fishes such as smallmouth bass *Micropterus dolomieu* (Steinhart et al. 2004). Nuisance species that are currently moving in the opposite direction (i.e., from the Mississippi River toward Lake Michigan via the Illinois Waterway) include the bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*. Both fishes have moved up the Illinois River and bighead carp have been captured 37 km (22 mi) downstream of the electric barrier and 87 km (52 mi) downstream from Lake Michigan (personal communication, July 19, 2002, Julia Wozniak, Senior Biologist, Midwest Generation, Chicago, IL), although no further movement upstream has been recorded.

These planktivores have the potential to compete with established sport fishes such as yellow perch for limited plankton resources in Lake Michigan and with the primary prey base of the important salmon fishery, the alewife. Although Kolar and Lodge (2002) used a modeling approach to predict that silver carp and the black carp *Mylopharyngodon piceus* (currently being considered for listing as an injurious species under the Lacey Act) would *not* be problems, they cautioned that these two species have well documented negative impacts in rivers and undesirable characteristics that were not considered in their models. The silver carp is a safety hazard to boaters, fishermen, and fisheries scientists because it grows to a large size (up to 150 lbs) and has a propensity to leap from the water when disturbed by boats or fishing gear (e.g., electrofishing gear). Injuries have been reported (J. Chick, Illinois Natural History Survey, personal communication). Black carp are molluscivores that might consume the remaining native mussels and snails of the Great Lakes, in addition to consuming the zebra mussels that foul the native mollusks.

To protect populations of valued species in both the Great Lakes and the Mississippi drainage basins, an electric dispersal barrier has been constructed in the Chicago Sanitary and Ship Canal by the U.S. Army Corps of Engineers to retard or stop the spread of harmful invasive fishes across the drainage boundary. The strength of the electric field increases from the outside to the middle of the barrier array. This allows the fish to detect the field before they are stunned. The fish are then able to turn back and avoid the barrier. The barrier was activated in April 2002 and provides an opportunity for rapid assessment and development of barrier technology that could be used wherever existing harmful organisms could spread through natural or man-made connections between waterbodies and basins.

Smaller electric barriers have been largely successful. Electric barriers were used to confine grass carp *Ctenopharyngodon idella* for aquatic weed control in two coves in Lake Seminole, Florida. Prior to use of the electric barriers, escapement ranged from 35-68% of the total number of fish tagged with radio transmitters and placed behind weirs in the coves. After addition of electric barriers to the weirs, no verified escapes occurred (Maceina et al. 1999). Mark-recapture studies in the Jordan River, Michigan indicated that a pulsed-DC electrical barrier set to a 2-ms pulse width and 10 pulses/s completely blocked the spawning migration of sea lampreys (Swink 1999). To assess the ability of an electrical barrier across an outlet stream to prevent migration into the Heron lakes basin in Minnesota, Verrill and Berry (1995) marked 1,600 common carp and native bigmouth buffalo *Ictiobus cyprinellus* with dart tags and released them downstream from the barrier. No tagged fish were among the 3,376 fish caught upstream from the barrier. Savino et al. (2001) judged an experimental electric barrier “functional” in deterring the downstream movement of round gobies as well as several native species in the Shiawassee River, Michigan. With the barrier on and using the prescribed electrical settings determined to inhibit fish passage in the laboratory, the only marked round gobies found below the barrier were dead. At reduced pulse durations, a few round gobies (mean = one/test) were found live below the barrier. Thus, electric barriers have proved effective with a wide range of fish species in relatively small applications.

Although these previous results are encouraging, the effectiveness of the barrier in the Chicago Sanitary and Ship Canal needs to be further tested to determine whether fish can pass through the electric field in the ‘electric shadow’ of commercial navigation traffic. This area of the canal is a heavily traveled commercial corridor, with at least 20 tows moving across the barrier on some days (personal observations). These steel-hulled barges have the potential to reduce the electric current immediately around their hulls, and to allow fish to pass through an otherwise impermeable barrier. Although the barrier contractor has done engineering studies to predict that barge passage should have no effect on barrier strength, this assumption has not been tested in the field.

Objectives

(1) Determine whether fish can move through the experimental electric barrier in the electric shadow created by barges.

(2) If shadowing occurs, suggest modifications for the proposed two-barrier system that will minimize or eliminate shadowing.

Methods

Objective 1. During November 11-14, 2003, we worked jointly with Smith Root, Inc (SRI) to test the effect of steel-hulled barges passing through the electric field of the dispersal barrier on fish swimming ability. This joint work was done as part of a request to SRI by the US Army Corps of Engineers to specifically determine whether a void would be created in the electric field by barge passage. This engineering information was needed to determine whether design changes were needed in a proposed second barrier. Thus, this engineering information, coupled with our biological observations, would provide solid evidence regarding the impact of barges on fish impairment.

We collected fish using 4-ft x 3-ft double-ended fyke nets with 1-in bar mesh set overnight in a littoral widening of the canal about 5 miles downstream of the barrier location. Fish were then transported to holding tanks at the dispersal barrier to await use in our study. Taxa used included catastomids, temperate basses *Morone* spp., and common carp *Cyprinus carpio*. The size of fish ranged from 170 mm to 580 mm. An individual fish generally experienced at least two runs.

For each run, we confined a single fish to an electrically neutral holding cage constructed of PVC, plastic mesh, and cable ties. The cage dimensions were 1 x 1 x 0.3 m. The cage was then lashed to the side of either a boat with a non-conductive (fiberglass) hull or a fully loaded barge with a conductive, steel hull. Runs were conducted in both upstream and downstream directions at normal barge operating speeds. We also varied the placement of the cage along the width of the canal to determine whether position in the canal changed fish responses to the electric field. All told, we conducted 12 runs in an upstream direction and 9 runs in a downstream direction. All runs were videotaped so that we could score fish responses to the electric field and relate them to distances upstream or downstream from the center of the electric barrier.

Basic data was recorded for each run from a combination of field data sheets, verbal cues throughout the videos, and visual observations made by the video viewer. The recorded information included date of the run, actual start and end time according to the video clock, direction of travel (upstream or downstream), the hull configuration (nonconductive, single barge, or double barge), location of vessel in the canal (east, west, center), location of the cage in relation to the hull, estimated speed of travel, species of fish, length of fish, and the number of runs that an individual fish had experienced. A total of twenty runs were filmed. One of these was broken down into two because it was disrupted mid-run and the direction of travel was changed.

Video footage collected in the field was viewed in the laboratory on a television screen during 2004-2005. Footage for each sample was viewed by the same person, at least once. Repeated viewings were conducted if the visibility was poor or if there were frequent changes in the behavior of the fish. We observed behavioral responses of the fish as they passed through the electric barrier alongside each hull. Data recorded were designed to quantify the behavior of the fish in relation to location and time within the electric field for each hull configuration. Each run was timed in the laboratory with a stop watch. The watch and video were paused to record location landmarks (example: 20 feet upstream of barrier), changes in the fish's behavior, and changes in the quality of visibility. Both verbal cues from the field crew recorded on the video and direct observations of the video were used to gather the data. We broke each run into a series of time segments based on distance moved and changes in the behavior of each fish. For each time segment, observations of the fish's behavior were described and given a score, or condition code, from 1 to 4 (Table 1). A score of 1 was assigned if a fish showed no signs of being affected. Corresponding behaviors included the following: maintaining position in current and uninhibited swimming. A score of 2 was assigned if a fish showed signs that it was affected. Corresponding behavioral descriptions included the following: short bursts of swimming, circling, darting, zigzagging, vibrating, and erratic swimming. A score of 3 was assigned if a fish lost equilibrium. Corresponding behaviors included the following: flashing, temporary rolling, and pinned to cage mesh but still showing movement. A score of 4 was assigned if a fish was immobilized. Corresponding behaviors included the following: immobile, upside down, no movement, pinned to cage mesh, and tetany.

In addition to the condition of the fish, two other characteristics of the behavior were noted. The first was the fish's orientation to the hull. Assuming no distortion, the electric field would have been perpendicular to the vessel. A fish should have received the weakest shock when it was parallel to the field and thus perpendicular to the hull and the water current. Orientation was recorded as perpendicular or parallel to the hull, or circling which was a common reaction. The second was the location of the fish in the cage (Table 2). The cage was divided into nine areas arbitrarily labeled 1-9. Areas are numbered referring to the following: area 1 to the center of the cage, area 2 to the corner of the leading side away from the boat, area 3 to the corner of the trailing side away from the boat, area 4 to the corner of the leading side near the boat, area 5 to the corner of the trailing side near the boat, area 6 to the middle of the leading side, area 7 to the middle of the trailing side, area 8 to the middle of the side away from the boat, and area 9 to the middle of the side near to the boat. This detail could be useful to determine how likely fish were to assume a position that minimized their distance from the hull, and it could provide insight into how greatly fish were affected by the snout water velocity (velocity of the water at fish's snout), which was much greater when traveling upstream.

We then took these data and analyzed the response of fish to our treatment factors. Specifically, we used SAS version 8.0 to conduct analysis of variance (ANOVA) to determine whether the distance traveled before the fish first showed signs of affectedness, total time affected, time immobilized, distance immobilized, and the time for immobilization to occur were affected by fish species, fish size, the direction of travel (upstream or downstream), position within the canal (east, middle, west), or the hull configuration (nonconductive, single barge, double barges). We analyzed differences among treatment levels using Tukey's Honestly Significant Difference post-hoc test. All results were considered significant at the $\alpha = 0.05$ level.

Objective 2. Engineers and biologists from SRI and we shared information about our results with each other. Based on the combined data, the information was presented to the Dispersal Barrier Advisory Panel to make them aware of our findings and to share possible design modifications for Barrier II.

Results

Objective 1. We tested three fish taxa, catastomids, temperate basses *Morone* spp., and common carp *Cyprinus carpio*. Size of the fish had no effect on any of the response variables (all $P>0.35$). Hence we do not consider fish size in any further analyses. Similarly, fish taxon did not affect any of our response parameters (all $P > 0.15$). No effect of location within the canal (left, center, or right) was observed when we tested for differences in the amount of time elapsed until the fish was first affected by the electric field. However, the direction of travel ($F_{1,6} = 8.17$; $P = 0.03$) and the hull configuration ($F_{2,6} = 14.95$; $P = 0.005$) did influence the distance traveled to first observed affectedness (Figure 1). There also was an interaction between these two factors ($F_{2,6} = 9.95$; $P = 0.01$). In particular, fish took longer to show symptoms of affectedness when moving downstream as compared to moving upstream (Tukey's HSD, $P<0.05$). When the tow was either 1 or 2 barges wide, the effects of the electric field on fish were delayed as compared to the nonconductive hull (Tukey's HSD, $P<0.05$). We saw no difference in time to affectedness when the barge train was either 1 or 2 barges wide (Tukey's HSD, $P>0.05$). The effect of the interaction resulted from a steady increase in the time to affectedness when moving downstream but no change in the time to affectedness when fish moved upstream.

When examining the time it took for fish to lose equilibrium in the electric field, direction of travel was unimportant ($F_{1,11} = 3.03$; $P = 0.11$), hull configuration was marginally significant ($F_{2,11} = 3.40$; $P = 0.07$), position within the canal was very important ($F_{2,11} = 9.46$; $P = 0.004$), and there was a strong canal position-hull configuration interaction ($F_{3,11} = 7.90$; $P = 0.004$). The strong interaction resulted from a very short time to lose equilibrium for fish in the treatment with the nonconductive hull when traveling down the center of the canal and from an extremely long time to lose equilibrium for fish traveling along the east side of the canal with a single barge (Figure 2). Two barges prolonged the time to loss of equilibrium as compared to the nonconductive hull (Tukey's HSD, $P< 0.05$). Only direction of travel affected the distance traveled from the start of the run until the fish lost equilibrium ($F_{1,11} = 6.33$; $P = 0.03$), with fish traveling upstream moving farther before losing equilibrium (Tukey's HSD $P < 0.05$).

No factor influenced the maximum level of affectedness reached. However, we did observe individual variation among fish in the maximum level of affectedness reached. Some fish never were fully immobilized when moving alongside a barge, whereas all fish in the treatment with the nonconductive hull were immobilized.

The amount of time that fish spent affected by the electric field was directly influenced by the location in the canal ($F_{2,11} = 6.33$; $P = 0.01$) and by the hull configuration ($F_{2,11} = 6.73$; $P = 0.01$). Furthermore, a strong canal position- hull configuration occurred ($F_{3,11} = 5.04$; $P = 0.02$) (Figure 3). Specifically, fish were affected longer when next to either a 1- or 2-barge configuration as compared to the vessel with the nonconductive hull (Tukey's HSD, $P < 0.05$). Fish were also affected longer when vessels traveled along the east side of the canal as compared to either the center or the west side of the canal (Tukey's HSD, $P < 0.05$). The interaction resulted from an extremely long time of affectedness for fish traveling with a single barge along the east side of the canal.

Although the time affected fish spent immobilized after contact with the electric field was not affected by any of our measured parameters, the distance an immobilized fish traveled was. The distance an immobilized fish traveled was affected by direction of travel ($F_{1,12} = 4.09$; $P = 0.07$) and hull configuration ($F_{2,12} = 7.44$; $P = 0.008$), and there was a strong configuration-direction interaction ($F_{2,12} = 5.08$; $P = 0.02$) (Figure 4). Specifically, fish next to the vessel with the nonconductive hull were immobilized for a longer distance than fish next to the single barge configuration (Tukey's HSD, $P < 0.05$). The interaction between canal side and hull configuration resulted from an extremely long time of immobilization for fish traveling upstream next to the nonconductive hull.

Objective 2.
Based on results from our joint tests and observations of field effectiveness with SRI, information regarding possible design modifications to Barrier II was considered at a meeting of the Dispersal Barrier Advisory Panel in May 2004. Results of this discussion were positive, resulting design changes to Barrier II that account for the warping of the electric field as it interacts with steel hulls. The design modification is to give the second barrier two components that will warp in opposite directions to eliminate the bubble of no electric field as a barge passes through the electric barrier. Not only will this modification prevent passage of fish near the barge hull, it also provides a longer field that eliminates the possibility of fish being pushed/pulled through the length of the field in towboat propeller wash. Once construction of Barrier II is complete (scheduled for Spring 2006), we expect to test how effective these modifications to the barrier have been.

Discussion

Effects of the electric dispersal barrier were very robust across three fish taxa and for fish > 150 mm TL. All taxa tested were immobilized by the electric field in the absence of barges. As fish moved closer to the electric field, they showed signs of affectedness more quickly when they approached moving in an upstream direction. This disparity may be related to the configuration of the electrodes within the dispersal barrier. The barrier is actually two barriers in one, with the upstream portion of the barrier designed to prevent movement of benthic fishes such as round goby *Neogobius melanostomus*. The downstream portion of the barrier energizes the entire water column. Thus, it is this portion of the barrier that we were testing in our experiments and explains why fish moving upstream were affected more quickly.

For the dispersal barrier field to be most effective, fish passing through the barrier should become immobilized. Our results demonstrated that fish swimming alongside barges took about three times longer to become immobilized than if they were swimming through the electric field without any substantial steel hull present. This disparity can be explained by the effect of a large moving steel mass on the electric field. Essentially, as a large steel hull approaches the barrier, the steel warps the field toward the hull. Thus, a fish immediately in front of the barge would be subjected to extremely high voltage. However, a fish swimming alongside or to the rear of the barge would find a shielded spot where the effects of the electric field would be substantially reduced or completely eliminated. We see the manifestation of this engineering effect through the longer time to immobilization of fish swimming next to the barges. However, once affected, the presence of barges lengthened the time that fish lost equilibrium or were immobilized. Thus, barges may increase the probability that fish may not be affected. Once fish were affected in the presence of barges, the effects were more severe and long-lived than in the treatment with the nonconductive hull.

Our results with respect to the position of the barges in the canal demonstrated few conclusive results. Although strong statistical interactions with canal position were generated when examining the response variables of time immobilized and distance immobilized, these results were driven by a couple of unusual responses. Generally, the field appeared stronger along the eastern canal wall, but no biologically meaningful differences were detected based on the position of travel within the canal.

One interesting result was that fish moving upstream traveled a longer distance before losing equilibrium than fish moving downstream. This may be because fish moving upstream were supported by the water velocity along its snout and sides. The relative increase in water velocity experienced by a fish moving upstream may make it appear to the viewer that it took longer for a fish to lose equilibrium, even though the fish was being supported by the water velocity.

Although we found no relationship between the maximum level of affectedness and any predictor variable, it is striking to note that some fish were never fully immobilized while swimming alongside barges, whereas all fish were immobilized alongside the vessel with the nonconductive hull. Certainly, most fish swimming alongside barges were immobilized, but given that some were not and all took longer to become affected as compared to counterparts swimming alongside the vessel with the nonconductive hull, it is clear that commercial navigation can diminish the impact of a dispersal barrier unless the barrier is specifically designed to take into consideration the effects of steel-hulled barges moving through the barrier. Fortunately in the case of the electric dispersal barrier in the Chicago Sanitary and Ship Canal, testing was completed on the demonstration barrier so that lessons learned could be applied to construction of the permanent dispersal barrier. The combination of our results and engineering tests conducted by the barrier builder allowed for a more effective design to be included in the permanent barrier.

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Condition code	State	Behavioral characteristics
1	Normal	Maintaining position in current, uninhibited swimming
2	Affected	Erratic swimming, circling, zigzagging, darting, vibrating, short bursts of swimming
3	Severely affected	Loss of equilibrium, flashing, temporary rolling, pinned to mesh but still showing movement.
4	Immobilized	Immobility, upside down, pinned to mesh with no effort to swim, tetany

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Table 1. Condition code scoring values and their corresponding state of affectedness and behavioral characteristics associated with each code. Condition code values were applied to each run based on video observations of fish behavior.

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Table 2. Location positions for fish inside the experimental cage, as seen from above. Water current entered the cage from leading side and exited cage through trailing side. The leading and trailing sides of the cage reversed, depending on the movement of the vessel upstream or downstream.

Corner of leading side near hull 4	Leading side middle 6	Corner of leading side away from hull 2
Middle near hull 9	Center 1	Middle away from hull 8
Corner of trailing side near hull 5	Trailing side middle 7	Corner of trailing side away from hull 3

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Figure 1. Distance (ft) that caged fish traveled along the Chicago Sanitary and Ship Canal before first showing signs of being affected by the electric field. Caged fish were placed immediately next to vessels with 0 (a non-conductive hull), 1, or 2 barges. Solid bars represent this distance traveled when moving downstream; solid bars represent the distance traveled when moving upstream.

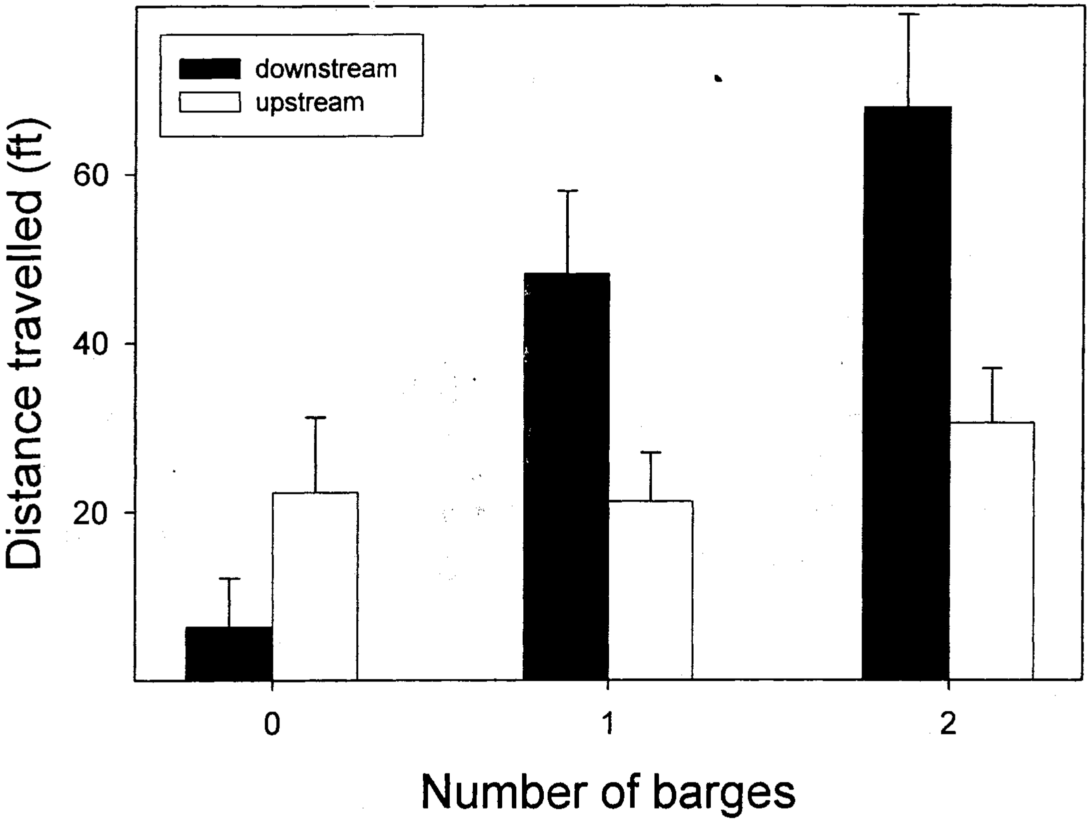

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Figure 2. Time (sec) needed for caged fish to lose equilibrium once exposed to the electric field when traveling along the east, middle, or west portion of the Chicago Sanitary and Ship Canal. Caged fish were placed immediately next to vessels with 0 (a non-conductive hull), 1, or 2 barges.

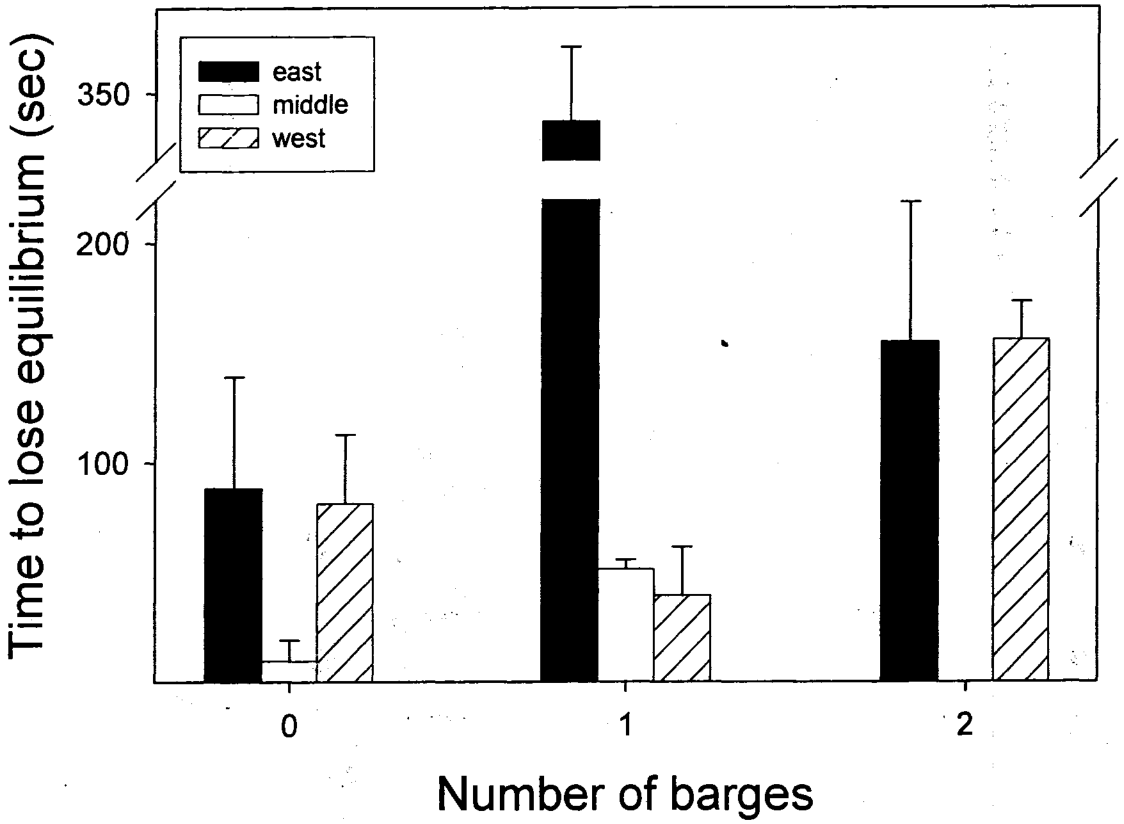

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Figure 3. Total amount of time (sec) that caged fish were affected by the electric field when traveling along the east, middle, or west portion of the Chicago Sanitary and Ship Canal. Caged fish were placed immediately next to vessels with 0 (a non-conductive hull), 1, or 2 barges.

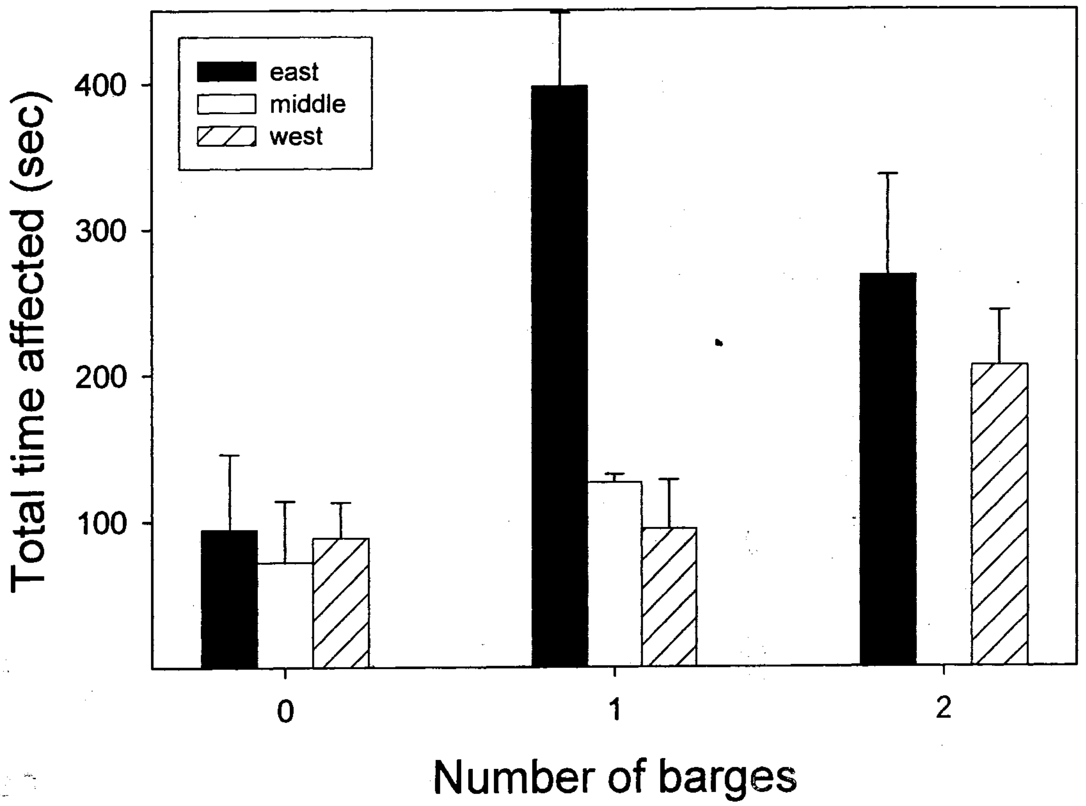

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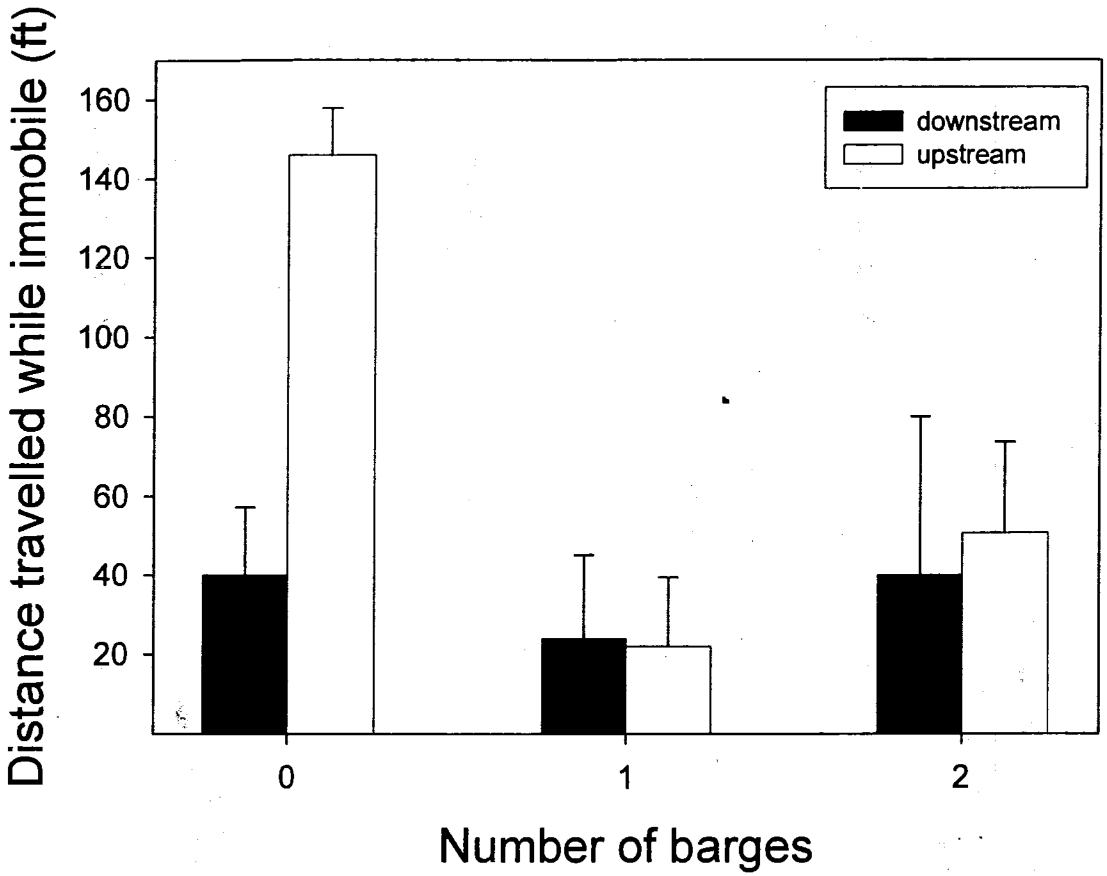
Figure 4. Distance (ft) that caged fish traveled along the Chicago Sanitary and Ship Canal while they were completely immobile after encountering the electric field. Caged fish were placed immediately next to vessels with 0 (a non-conductive hull), 1, or 2 barges. Solid bars represent this distance traveled when moving downstream; solid bars represent the distance traveled when moving upstream.


Distance travelled while immobile (ft)
160
140
120
100
80
60
40
20
0
1
2
Number of barges
downstream
upstream