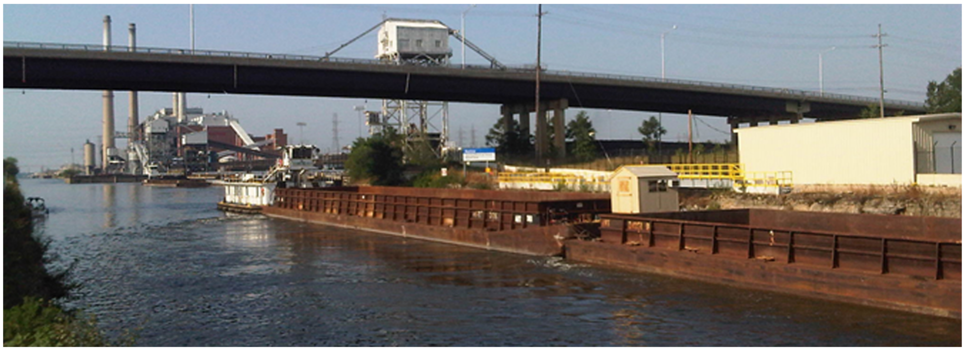
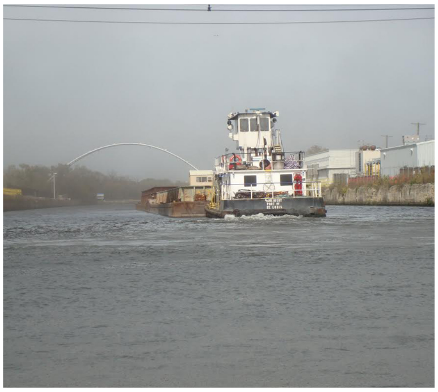
U.S. Fish & Wildlife Service - Midwest Region

Fisheries Program

Preliminary Results of Fish-Barge Interactions at the Electric Dispersal Barrier in the Chicago Sanitary and Ship Canal





Report Prepared By:

Aaron D. Parker and Samuel T. Finney
Department of the Interior
U.S. Fish and Wildlife Service
Carterville Fish and Wildlife Conservation Office, Illinois

December 2013

Executive Summary

Beginning in 2012, the U. S. Fish and Wildlife Service (USFWS) Carterville Fish and Wildlife Conservation Office (FWCO) has been performing fish-barge interaction evaluations at the electric dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC). Initial work consisted of placing wild-caught fish within a non-conductive cage either alongside different parts of a barge or within various barge junction wedges of water. The fish were then moved through the barrier, and the effect of the barrier on the fish (incapacitated or not incapacitated) was recorded with a camcorder that was mounted above the cage. Fish that were used in the caged fish trials were primarily Gizzard Shad (*Dorosoma cepedianum*), but Common Carp (*Cyprinus carpio*) and Freshwater Drum (*Aplodinotus grunniens*) were used in some trials as well, depending on availability.

All caged fish that were moved along the side, front, and the pocket eddy (water movement that forms behind the barge sterns where a tow vessel is centered on two parallel barges pushing them forward) were incapacitated. Caged fish within rake-to-rake and rake-to-tow junction wedges were all incapacitated as well. However, only one large fish that was placed in the wedge of water between a rake-to-box junction was incapacitated. The fish that were not incapacitated, in the rake-to-box junction wedge, were Gizzard Shad, Freshwater Drum, and Common Carp ranging from 14.2 – 51.1 cm total length. This was a result of reduced in-water voltage in that junction wedge.

Later we used unconfined Gizzard Shad (not placed in cages) that were tethered to floats. Gizzard Shad were either placed directly into the various barge junctions as the barge approached the barrier, or deployed in the water across the width of the CSSC, below the active barrier, prior to a barge traversing it. All configurations yielded some percentage of entrainment beyond the barriers, save rake-to-tow, when fish were directly placed in this space. The sizes of the 41 fish that were entrained beyond the barriers (21 after direct deployment into a junction wedge, 20 after deployment below the barrier) ranged in size from 9.9 – 24.6 cm total length. The percentage of fish that crossed varied depending on deployment method and barge configuration. Directly placing the fish within rake-to-box and rake-to-rake junction wedges yielded the largest percentage of crossings (14% and 13 % respectively).

However, after deploying the fish below the barriers, prior to a barge strike, the pocket eddies yielded the greatest amount of entrainment beyond the barrier (8%). The rake-to-box and rake-to-tow junction wedges yielded similar crossing percentages following a barge strike (5% and 4% respectively). The fish that were struck by barges slowly moved downstream along the bottom of the barge before re-surfacing in a wedge or eddy. The rake-to-rake configuration yielded the lowest percentage of fish crossings (2%), when fish were deployed in front of the barges, because the boxed ends of the barges were moving forward, which displaced most of the fish to the side. The fish that crossed did so by swimming into a small void space between the barges at the bow. Later, we had a tow vessel pull a rake-to-rake barge configuration across the

barrier. This eliminated the small void space, however, the tow vessel moved very slowly across the barrier and stalled several times. Thus, this method of traversing the barrier, is likely not feasible for commercial navigation.

Introduction

Beginning in the summer of 2012, the U. S. Fish and Wildlife Service (USFWS) Carterville Fish and Wildlife Conservation Office (FWCO) has been performing fish-barge interaction evaluations at the electric dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC). Concerns about large, metal-hulled vessels facilitating barrier crossings by fish were first raised by Sparks et al. (2010) and Dettmers et al. (2005). Sparks et al. (2010) and Dettmers et al. (2005) directly tested the effectiveness of the first electrical barrier, the Demonstration Barrier. Sparks et al. (2010) released 130 Common Carp (*Cyprinus carpio*) with surgically-implanted, combined radio-and-acoustic transmitters downstream of the Demonstration Barrier. Movements were recorded from 2002 to 2006, and during that time one fish was able to cross the Demonstration Barrier on April 3, 2003, which was operating at 0.39V/cm, 5 Hz, 4ms (0.39 V/cm). This crossing was determined to have occurred at the same time that a steel-hulled barge traversed the barrier, which gave rise to speculation that the fish may have either been involuntarily entrained by the barge, or that the barge may have distorted the electrical field enough that the fish could have swam alongside the barge in an electrical void. However, after the crossing, the fish remained in the same area that was 3 km upstream of the barrier, indicating that the fish was either dead when it crossed the barrier or died shortly after crossing (Sparks et al. 2010).

During November 11-14, 2003, Dettmers et al. (2005) passed caged fish alongside a barge through the Demonstration Barrier. Again, the barrier was operating at 0.39 V/in. Fish used were Catastomidae (sucker) species, Moronidae (temperate basses) species, and Common Carp. They found that these fishes took longer to exhibit effects from the barrier moving downstream than upstream through the barrier. The effects of the electrical field were also delayed when caged fish swam alongside conductive (steel) barge hulls compared to non-conductive (fiberglass) hulls. Some caged fish that were towed along the steel-hulled barges were never incapacitated as they swam through the barrier. The fishes that did not become incapacitated were < 150 mm total length.

Dettmers et al. (2005) noted that metal-hulled barges warped the electrical field of the barrier and created void spaces that fish could swim along and not be affected by the electricity. Besides distorting the electric field, barges also create a complex suite of hydrodynamic water motions (detailed in Figure 1) as they navigate through riverine waterways (Bhowmik and Mazumder 1990; Maynord and Siemsen 1990; Wolter and Arlinghaus 2003). The direct (Killgore et al. 2001; Gutreuter et al. 2003; Killgore et al. 2011) and indirect (Wolter and Arlinghaus 2004; Gutreuter et al. 2006; Kucera-Hirzinger et al. 2009) impacts of tow-barge vessel navigation on fish has been well investigated. However, the actual distances that fish are physically displaced by barges, especially near electrical barriers, is a topic that warrants further investigation.

Briefly, as a barge moves through the water past a fixed point, it first creates a bow current in front of the vessel followed by a bow wave. This bow wave creates a rise in the water level in front of the vessel, which causes a water drawdown along the hull of the vessel. This drawdown then creates a return velocity of water moving in the opposite direction of the vessel. The water level then rebounds at the stern of the barge, and the water directly behind the stern travels in the direction of the barge vessel as wake flow. Finally, the water directly behind the tow vessel is moved away from the tow by the propeller jet velocity (Figure 1; Bhowmik and Mazumder 1990; Maynord and Siemsen 1990; Wolter and Arlinghaus 2003). The end result of a tow-barge vessel passing a fixed point is accelerated downstream flow if the vessel was navigating upstream, or a temporary reverse of flow if the vessel is navigating downstream (Bhowmik 1991). The magnitude and extent of these water movements is dependent on the size of the vessel, relative to the water body, and the speed at which it is travelling (Wolter and Arlinghaus 2003). These barge-induced water movements are more exaggerated in confined channels. A confined channel is one which has a simple shape and has a significant cross-sectional area taken up by navigating vessels (Martin 1997; Maynord 2004; Taylor et al. 2007), as opposed to a large riverine system with sloped banks that can attenuate wave and flow energy. The section of the CSSC that encompasses the barrier system is rectangular in cross-sectional shape and is a confined channel. Another noteworthy aspect of the complex hydrodynamics created by barges is the wedges of water between barge junctions (Figure 1G). These wedges of water typically exhibit weak recirculation patterns that are isolated from the adjacent water. The magnitude of water movement and isolation in these wedges depends on the barge junction used (Figure 2C-E), but some can transport debris for long distances.

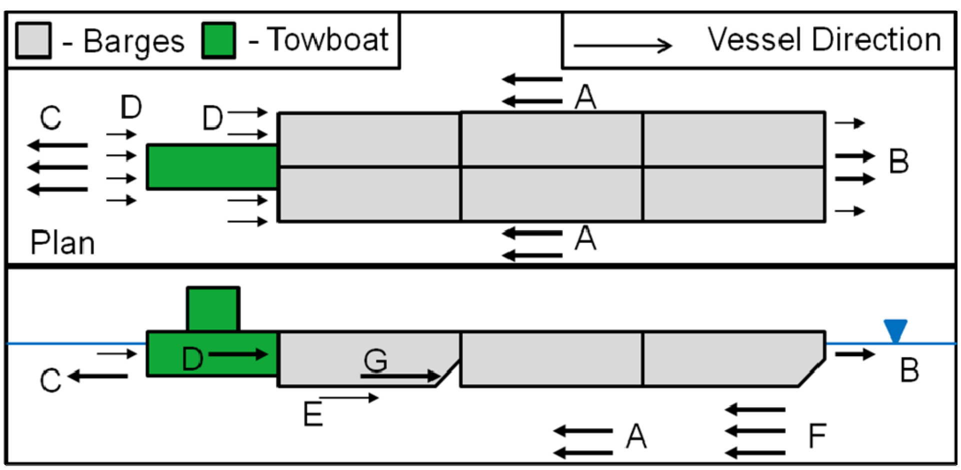


Figure 1. Water motions around tows moving left to right in confined channels. A = return velocity, B = bow wave, C = propeller jet, D = wake flow, E = flow in boundary layer along hull, F = displacement flow at bow between hull and channel bottom having short duration and G = pocket recirculation. Figure created by the USACE Engineer Research and Development Center – Coastal and Hydraulics Laboratory and reprinted with permission.

To date, the Carterville FWCO has worked with the U. S. Army Corps of Engineers (USACE)-Chicago District and the USACE Champaign Construction Engineering and Research Laboratory (CERL) on six separate occasions evaluating the interactions between fish and large metal barges traversing the electric barrier system within the CSSC. The purpose of this interim report is to provide a brief summary of the results of this work.

Materials and Methods

In an attempt to understand the hydraulic and electrical effects on fishes near barges traversing the barrier, initial work in 2012 consisted of placing wild-caught fish within non-conductive cages either alongside different parts of a barge (four trials along the side and two trials at the barge front; Figure 2A) or within the wedge of water created between various barge junctions (ten trials in the rake-to-box, nine trials in the rake-to-rake, and four trials in the rake-to-tow configurations; Figure. 2B-E). The barge and fish were then moved through the barrier, and the effect of the barrier on the fish (incapacitated or not incapacitated) was recorded with a video camera that was mounted above the cage. Incapacitation was defined as the complete cessation of all movement by the fish, which caused it to either be impinged against the downstream end of the cage or lay motionless on the bottom of the cage. All fish used in the barge trials were measured after each trial was complete in order to reduce handling stress. Fish that were used in the trials were primarily Gizzard Shad (*Dorosoma cepedianum*), but Common Carp and Freshwater Drum (*Aplodinotus grunniens*) were used in some trials, depending on availability. Specifically, we used progressively larger fish in subsequent runs, generally beginning with Gizzard Shad and moving to Freshwater Drum and Common Carp, to investigate if a size threshold existed at which fish in each tested configuration would be incapacitated. The first caged-fish evaluations were performed with Barrier IIB operating, whereas during the second caged-fish evaluation both Barriers IIA and IIB were operating. All trial runs began below the barrier in non-electrified water and ended after the entire barge vessel completely traversed Barrier IIB. All fish that were used for these evaluations were collected via electrofishing within the CSSC.

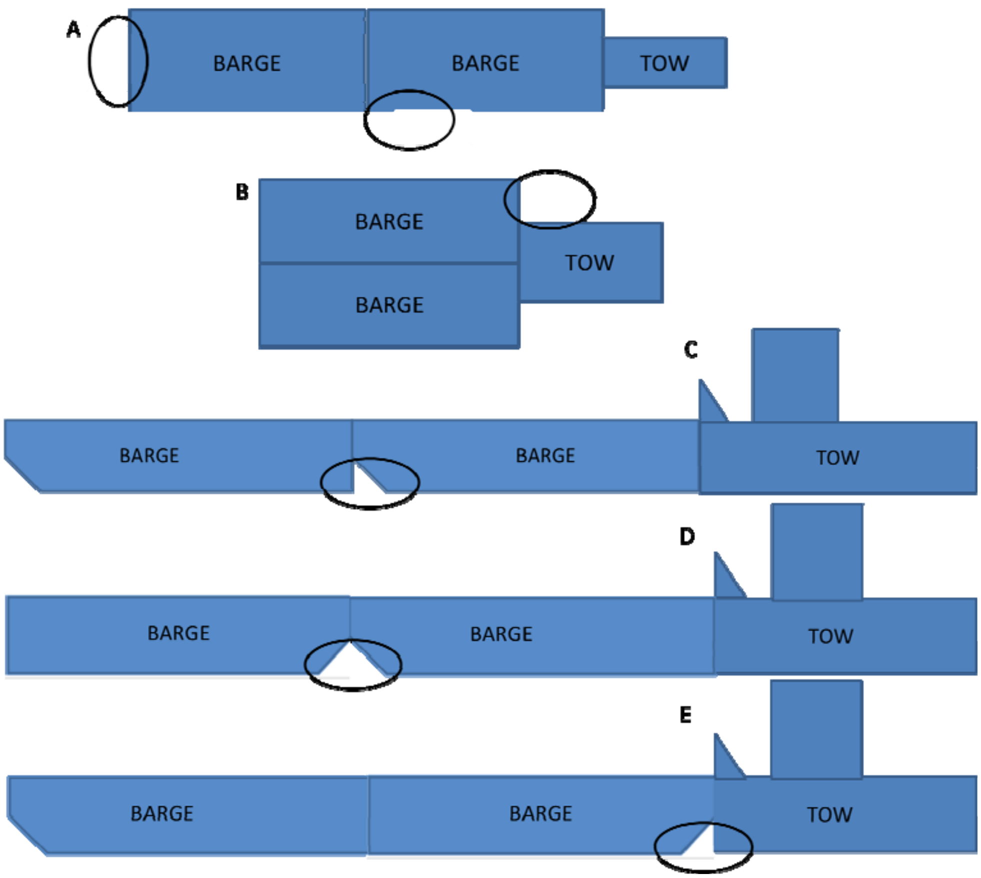


Figure 2. Various barge configurations used for fish-barge interaction work. Circles denote locations where fish were placed in a cage or directly deployed into the water, without a cage, after being tagged. These junction wedges served as potential void spaces to transport unconfined fish that had been deployed in front of the barge, after the barge struck them. A = locations of the cage placed along the side and in front of series configured barges. B = parallel barge configuration in which the tow vessel is centered on the two barges. As the barges move forward a "pocket eddy," of water forms in the wake flow that can move debris forward with the barge. C = rake-to-box configuration. D = rake-to-rake configuration. E = rake-to-tow configuration.

After all of the caged-fish trials were completed in the fall of 2012, we focused solely on using tethered, unconfined Gizzard Shad (not placed in cages) to evaluate fish-barge interactions. Unconfined, tethered Gizzard Shad were used for one day in October 2012 to assess the value of the new methodology. After a successful evaluation with the unconfined, tethered fish in October 2012, all evaluations in 2013 utilized this methodology. Fish were tethered to high-visibility floats using 0.45 kg tensile strength, 0.06 mm diameter, dynema line to enable recovery of the fish, similar to methods described in Hasler (1958) and Sass and Ruebush (2010). The floats were attached to 1 m of dynema line. To attach the line to the fish, a sewing needle was used to thread the line through the soft tissue between the premaxillary and maxillary bones of the mouth and two overhand knots were tied. During each trial, ten tethered Gizzard Shad were either placed directly into the various barge junctions as the barge was approaching the barrier, or deployed in the water across the width of the CSSC, below the active barrier prior to a barge approaching and traversing it. Barges approached the deployed fish in two-wide parallel (Figure 2B), rake-to-box (Figure 2C), rake-to-rake (Figure 2D), and rake-to-tow (Figure 2E) configurations. The two different methods of the unconfined-fish placement were employed to investigate two different sets of questions: 1) by placing the unconfined, tethered fish directly into the various junction wedges, we were evaluating the likelihood of a fish remaining within that wedge of water either on its own volition (in the event that it did not become incapacitated) or as a result of the hydrodynamics within the wedge retaining the fish after it was incapacitated; and 2) we placed tethered fish below the active barrier to address the likelihood of a fish initially becoming entrained by the barge and then remaining within a junction wedge as it moves through the barrier. After the barge completely traversed the barrier system, the tagged fish were collected and their locations recorded. If fish were found above the barrier but the tether was entangled on the barge, or if any fish entangled their tethers together with other fish tethers, those fish were not recorded as crossing since the entanglement may have facilitated the crossing.

In November 2013, three different unconventional modes of barge navigation were employed to investigate alternative methods to reducing the possibility of fish entrainment. The first method consisted of having a tow vessel pull, rather than push, a rake-to-rake barge configuration upstream after fish were deployed below the active barrier. This was done in order to eliminate a small void space (Figure 4), which had facilitated earlier fish crossings when the barges were pushed upstream. We also directly placed tethered fish within the rake-to-box junction wedge (Figure 2C) as the barge was approaching the barrier; however, during three trials, the barge stopped all movement and held position below the active barrier for two minutes. This was done in an attempt to allow the fish to swim out of the junction wedge on their own volition prior to entering the barrier. Four additional trials were also performed in which Gizzard Shad were placed into the rake-to-box junction wedge; however, during these navigations, the barges took an angled approach towards the barrier and alternated angles in a “zig-zag” pattern. This was done in an attempt to increase the water flow moving through the rake-to-box junction wedge and flush out the fish.

Results and Discussion

All caged fish along the side (4 trials, 19 fish in total) and in the front of a barge (2 trials, 10 fish in total; Figure 2A) were incapacitated as the barge traversed the barrier. All caged fish that were placed in the pocket eddy of a parallel configuration (3 trials, 15 fish in total; Figure 2B) were incapacitated (Table 1). However, there was a minimal amount of flow in the eddy, and unlike the fish in the bow or side, these incapacitated fish were not impinged against the back of the cage. This raised concerns that stunned fish may still remain entrained in the eddy beyond the barrier. Also of concern were wild (not stocked by USFWS) Mosquitofish (*Gambusia* spp.) that remained within the junction on their own volition beyond the barrier in this eddy during the barge runs. We confirmed that what we observed were indeed Mosquitofish by netting and identifying some of the fish when the barge was stopped.

Of the 36 caged fish that were placed in the wedge of water in the rake-to-box configuration (10 trial runs; Figure 1C), only one was incapacitated. The one fish that was incapacitated was a large common carp (Table 1). Similar to the pocket eddy results, a small wild fish remained within the junction on its own volition past the barrier in this wedge of water during one run. One possible explanation of this phenomenon was noted by CERL workers measuring the in-water voltage within the cage. They confirmed that the voltage between the rake-to-box junction wedge was reduced as the barge traversed the barrier from the normal operating voltage of 0.91 V/cm to 0.06 V/cm.

All caged fish that were placed in the rake-to-rake junction (9 trials; 37 fish in total; Figure 2D), appeared to be briefly incapacitated when they were directly over the strongest part of the barrier. CERL researchers confirmed that at the time when the fish were briefly incapacitated there was a spike of in-water voltage directly over the strongest part of the barrier. Caged fish that were placed in the wedge of water between a rake-to-tow vessel configuration (4 trials; 16 fish in total; Figure 2E) were all incapacitated (Table 1). Of all of the junction wedges where in-water voltage was measured by CERL workers, the rake-to-tow wedge had the highest level, approximately 0.39V/cm, compared to the normal operating voltage of 0.91 V/cm.

During the unconfined, tethered fish trials, the results varied depending on fish deployment method used and the barge configuration (Figure 3). All barge configurations evaluated yielded some percentage of entrainment beyond the barriers, except for rake-to-tow, when fish were directly placed in that junction wedge. The 41 Gizzard Shad entrained beyond the barriers ranged in size from 9.9 – 24.7 cm TL. Instances of entrainment beyond the barrier occurred both after direct placement into a junction wedge or deployment below the barrier. Of the 340 Gizzard Shad used during the tethered fish evaluations, 21 crossed after direct placement into a junction wedge whereas 20 crossed after deployment below the barrier. (Note: measurements were not made on all fish that crossed the barrier. In three cases, tethered fish were observed beyond the barrier but were able to elude recapture by field personnel. In these cases, only the location coordinates were recorded where they were observed.)

Table 1. Numbers and sizes of different fish species that were caged along different parts of a barge and within barge junction wedges with one and two barriers operating. A length was not obtained for the one common carp that did become incapacitated, in the rake-to-box junction, because it escaped confinement after traversing the barrier.

Cage placement	Fish species	Number used	Size range (cm; TL)	Incapacitated?
		July 2012, Barrier IIB operating		
Side of barge	Gizzard shad	18	5.8 – 34.3	YES
Side of barge	Common carp	1	53.3	YES
Front of barge	Gizzard shad	10	5.8 - 26.2	YES
Barge stern "pocket eddy"	Gizzard shad	15	14.2 - 23.9	YES
Rake-to-box junction	Gizzard shad	15	16.8 - 25.7	NO
Rake-to-box junction	Common carp	2	41.2 - 51.1	NO
Rake-to-box junction	Freshwater drum	1	37.1	NO
		October 2012, Barriers IIA and IIB operating		
Rake-to-tow junction	Gizzard shad	15	15.0 - 21.3	YES
Rake-to-tow junction	Freshwater drum	1	37.1	YES
Rake-to-rake junction	Gizzard shad	35	10.4 - 29.2	YES
Rake-to-rake junction	Common carp	1	43.9	YES
Rake-to-rake junction	Freshwater drum	1	34.5	YES
Rake-to-box junction	Gizzard shad	15	16.0 - 22.6	NO
Rake-to-box junction	Common carp	1	37.1	NO
Rake-to-box junction	Common carp	1	~75*	YES
Rake-to-box junction	Freshwater drum	1	38.1	NO

*Estimated length. Fish escaped confinement after trial run.

Both deployment methods yielded similar percentages of fish crossings beyond the barrier, via the pocket eddy, when the barges were in a parallel configuration. This suggests a similar likelihood of fish remaining within the pocket eddy either when placed in this space, or upon surfacing in this space after a barge strike (observed during tethered fish evaluations when they were run over by a moving barge). Small, wild Mosquitofish observed being transported through the barrier in this pocket eddy further supports the idea that fish may remain in this space on their own volition. The percentage of fish that remained within the rake-to-box junction wedge when placed directly in this space was higher than those that were entrained within it following a barge strike. Evidence of fish entering and remaining within the rake-to-box wedge on their own volition was also supported by the observation of a small wild fish that was entrained across the barriers during our caged-fish evaluations.

Placing fish directly into the rake-to-tow junction wedge yielded no fish crossings. This was most likely because of the high amount of water turbulence between the tow and the barge vessel. After the fish were placed within the rake-to-tow junction wedge, the fish and tethers were observed immediately moving in an uncharacteristic manner in this turbulent area until they eventually were flushed out behind the barge. Some of the fish did remain within the small pocket eddy for a short period before they exited this space, prior to the vessel reaching the barrier. The difference between entrainment percentages in the rake-to-tow configuration may be explained by the number of barges that the tow vessel was centered on. When we directly placed the fish into the rake-to-tow junction wedge, the tow was centered on one barge vessel (see Figure 2A). However, when the fish were deployed below the barrier before barge strikes, the tow vessel was centered on a two-wide rake-to-tow configuration (see Figure 2B for an example of a tow centered on a two-wide barge configuration), which created a larger pocket eddy behind the barge than the one-wide configuration and entrained some fish past the barrier. Therefore, the fish crossings in that configuration were most likely a result of the pocket eddy formed by the two-wide configuration as opposed to the smaller junction wedge between the tow and the barges. The different placement methods were performed during two separate time periods, in which different numbers of barge vessels were contracted.

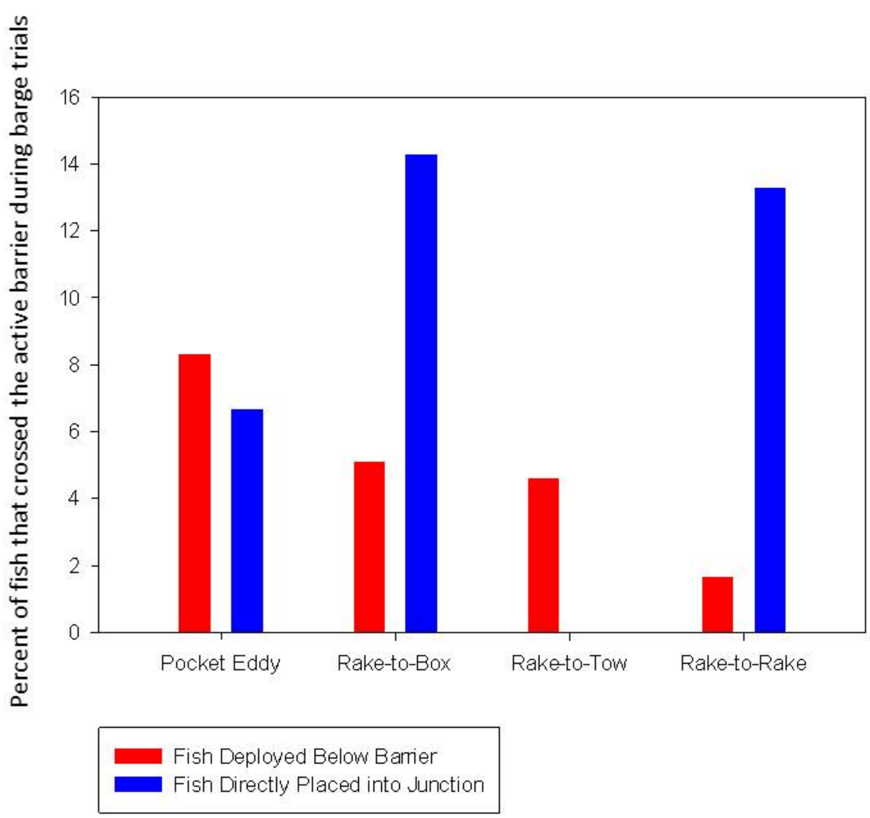


Figure 3. Percentages of live tethered fish that crossed the barrier system via different barge junction configurations and fish deployment methodologies.

The rake-to-rake configuration showed the largest discrepancy in the number of fish crossings as a result of deployment method. Some fish remained within the rake-to-rake junction wedge when directly placed in this space and subsequently crossed the barrier. However, only a small percentage of fish crossed the barrier via barge-strike entrainment. When the barges were attached in a rake-to-rake junction, the square end of the lead barges were what the fish first encountered as the barge tow moved upstream. Most of the fish were observed being displaced to the side of the barge tow before it moved to the barriers. There were only two fish that became entrained beyond the barriers in this instance by swimming into a small void space between the two square ends of the barge (Figure 4). No fish that were deployed below the barrier ended up entrained within the rake-to-rake junction wedge. These results suggest that while the rake-to-rake junction wedge is conducive to entraining some fish past the barrier, the possibility of fish initially becoming entrained within that wedge appears low.

We were able to perform nine trials using unconventional modes of barge navigation in order to investigate possible modes of transportation to reduce the possibility of fish entrainment. Twenty fish were deployed in front of the rake-to-rake configuration as the barges were pulled upstream by the tow vessel. None of the fish were entrained beyond the barrier; however, that method of transport will most likely not be a feasible alternative for commercial navigation traversing the barrier. The first trial run, which consisted of the barges moving through the entire barrier system, took over an hour to complete (as opposed to a normal passage time of around five minutes). This was because the current in the canal, as well as the propeller jet from the tow vessel flowing against the boxed ends of the barges created more drag. The second run had to be prematurely interrupted after the tow vessel stalled several times and could no longer pull the barges forward. Three trial runs were performed in which the barge vessel ceased movement for two minutes prior to entering the barrier. Of the 30 fish that were used, 3 of them remained within the rake-to-box junction wedge for the entire two minutes, and were then entrained beyond the barrier. Four trials were performed in which the barge alternated approach angles in a zig-zag pattern across the barrier. Of the 40 fish that were used, 6 of those fish remained within the rake-to-box junction wedge and were entrained beyond the barrier. We were able to observe some of these fish swimming within the junction wedge either as it was moving or when the barge stopped, indicating that the fish remained within the rake-to-box junction on their own volition (as opposed to involuntarily after being incapacitated). The sizes of the Gizzard Shad that crossed the barrier during our unconventional navigation approaches ranged from 21 – 26.5 cm total length.

Figure 4. Picture of the front of a rake-to-rake barge configuration traversing the electrical barrier with the square ends in the front. The circle denotes the small void space that two live fish swam into and remained inside beyond the barrier.

All fish, during all trials, were alive when recovered. We observed several instances where the fish did not reappear until after the barge had traversed the barrier, suggesting that the fish were entrained along the bottom of the barge vessel as it crossed the barrier. This would have placed the fish deeper in the water column, 2.7 m closer to the barrier arrays on the bottom of the canal where the electrical fields are magnified (Holliman 2011). According to CERL researchers, the fish would be exposed to electrical fields as high as 2.76 V/cm at this depth.

Based on our findings, all barge junctions have the capacity to provide a transport mechanism for fish to cross the barrier. However, the level to which these barge junctions may entrain individual fish seems to vary. Barge configurations with raked front ends appear to entrain the most fish; whereas, a configuration with square ends moving forward appeared to entrain the least amount of fish. In the event that fish near the barrier system are struck by a barge with a raked front end, the results suggest that the fish will likely be moved along the underside of the barge towards the stern until it encounters a junction wedge or pocket eddy at the barge's stern. At that point the hydrology around these junctions may entrain the fish, where it would likely experience low hydraulic flow and diminished voltage, as the barge continues to move across the barrier system.

Others have shown that fish are entrained by towboats (Gutreuter et al. 2003; Miranda and Killgore 2013), including Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*; Killgore et al. 2011). These studies took place in large, wide rivers that are very different from the narrow and confined CSSC. Killgore et al. (2011) found that, at times, fish entrainment was highest in narrow sections of water with slow velocity suggesting that fish entrainment in the CSSC may be higher when compared to a natural system. Undoubtedly, the electrical barrier system in the CSSC presents a different barge-fish interaction scenario than what others have studied given the presence of a large electric barrier. The barrier may act as a "third wall" in the canal system that does not allow fish to escape from oncoming barge vessels.

Or as fish swim to avoid barge traffic, they could move inadvertently into the barrier making them more susceptible to barge-induced entrainment. In an associated study, fish behavior was recorded within the barrier system using dual-frequency identification SONAR (DIDSON). The results of that study suggest that fish will accumulate below the barrier and persistently probe it (Parker et al. 2013). This accumulation of fish in the middle of an open channel again presents a very different scenario than studies in natural rivers without electric barriers. Ultimately, with increased fish assemblages in the vicinity, the barrier itself may limit the places that fish can escape from an oncoming barge and provide further opportunity for fish incapacitation and possible entrainment.

As mentioned above, DIDSON sampling has recorded large accumulations of wild fish immediately below the barriers, including small fish, approximately 5 - 10 cm, within the zone of ultimate field strength (Parker et al. 2013). At that location, these small fish are estimated to be approximately 2 m away from crossing the barrier. In the tethered fish evaluations, fish were deployed immediately below the wide arrays of the barrier, where in-water voltage is minimal (~ 0.08 V/cm). However, the fish were observed swimming away from the barrier and consequently towards the barge as it moved upstream. Because of this situation, the actual fish-barge strikes occurred over 100 m away from the barrier. Yet some of these fish were still entrained beyond it. Based on the results of the DIDSON sampling, which has shown large accumulations of fish in and directly below the electric field of the barrier, coupled with the possibility of the barges to entrain fish for long distances, we would expect that a fish struck by a barge in closer proximity to the barrier would increase the likelihood of that fish being entrained across the barrier.

An important aspect of these results is that they do not take into account the number of deployed fish that were never struck by the barge. Some fish avoided the barges, and other barge-fish interactions were not able to be observed due to safety precautions. Because these observations could not be made, we cannot quantify the proportion of deployed fish that were struck by the barge, which may affect the number of entrainments observed for the deployed fish method.

Another important consideration when interpreting these results is the effects that the attached tethers and floats may have on the swimming ability of the fish. The use of tethered floats has been used to evaluate the movements of small, aquatic animals by others (Hasler et al. 1958; Witherington 1995; Okuyama et al. 2009; Sass and Ruebush 2010); however, we are unaware of any research that has addressed the effects that the floats may have on the swimming ability of fish. Although the floats and tethers may have contributed to the fish being struck by the barge, there is also research to suggest that un-tethered, wild fish are frequently struck by barges as well (Gutreuter et al. 2003; Killgore et al. 2011; Miranda and Killgore 2013). Personnel in the field noted during the evaluations that many fish were able to pull the floats and tethers under water and were in some cases able to elude recapture. Furthermore, after a tagged fish is struck by a barge, the force of the moving barge likely has more influence on the body of the fish as opposed to the influence of the float and tether. We recognize that the tethers and floats may have had some effect on results, but these effects would likely be minimal in regards to the duration of entrainment. We also deployed floats that were unattached to fish, and floats that were attached to recently deceased fish as part of a broader comparison of the mechanisms affecting fish-barge interactions. The results of those comparisons in the future may answer some questions about the effect that the floats and tethers have on fish.

The current barrier operating parameters are based on laboratory trials using Bighead Carp (Holliman 2011). Our studies primarily used Gizzard Shad that may not exhibit the same response to the electric barrier as Bighead Carp. Currently, plans are underway with USACE to evaluate the comparability of Gizzard Shad and Bighead Carp susceptibility to the current barrier settings, which may help us further clarify and interpret the results of this study.

The findings of this study, in conjunction with concurrent work completed by our project partners have triggered discussions regarding the likelihood of barge facilitated barrier crossings and possible preventative measures that could be put in place to further protect against aquatic invasive species. We continue to work with our partners towards better understanding barrier-barge interactions and their possible impacts on aquatic organism movements within the CSSC.

Acknowledgments

This work was funded by the Great Lakes Restoration Initiative. Support was provided by USACE Chicago District, USACE Champaign CERL, and the US Coast Guard – Lake Michigan Sector.

References

Bhowmik, N. and B. S. Mazumder. 1990. Physical forces generated by barge-tow traffic within a navigable waterway. Pages 604-609 in Chang, H. H. and J. C. Hill, editors. Hydraulic engineering. American Society of Civil Engineers, New York.

Bhowmik, N. G. 1991. Hydraulic changes in rivers due to navigation. Pages 33-40 in Fan, S.-S. and Kuo, Y.-H., editors. Proceedings from the 5th Federal Interagency Sedimentation Conference.

Dettmers, J. M., B.A. Boisvert, T. Barkley, and R.E. Sparks. 2005. Potential impact of steel-hulled barges on movement of fish across an electric barrier to prevent the entry of invasive carp into Lake Michigan. October 2003 – September 2005. Completion Report for US FWS; INT FWS 301812J227.

Gutreuter, S., J. M. Dettmers, and D. H. Wahl. 2003. Estimating mortality rates of adult fish from entrainment through the propellers of river towboats. Transactions of the American Fisheries Society 132:646-661

Gutreuter, S., J. M. Vallazza, and B. C. Knights. 2006. Persistent disturbance by commercial navigation alters the relative abundance of channel-dwelling fishes in a large river. Canadian Journal of Fisheries and Aquatic Sciences 63:2418-2433.

Hasler, A. D., R. M. Horrall, W. J. Wisby, and W. Braemer. 1958. Sun-orientation and homing in fishes. Limnology and Oceanography 4:353-361.

Holliman, F. M. 2011. Operational protocols for electric barriers on the Chicago Sanitary and Ship Canal: influence of electrical characteristics, water conductivity, fish behavior, and water velocity on risk for breach by small silver and bighead carp. March, 2011, Smith-Root Inc, Vancouver, WA.

Killgore, K. J., S. T. Maynord, M. D. Chan, and R. P. Morgan Jr. 2001. Evaluation of propeller-induced mortality on early life stages of selected fish species. North American Journal of Fisheries Management 21:947-955.

Killgore, K. J., L. E. Miranda, C. E. Murphy, D. M. Wolff, J. J. Hoover, T. M. Keevin, S. T. Maynord, and M. A. Cornish. 2011. Fish entrainment rates through towboat propellers in the upper Mississippi and Illinois Rivers. Transactions of the American Fisheries Society 140:570-581.

Kucera-Hirzinger, V., E. Schludermann, H. Zornig, A. Weissenbacher, M. Schabuss, and F. Schiemer. 2009. Potential effects of navigation-induced wave wash on the early life history stages of riverine fish. Aquatic Sciences 71:94-102.

Martin, S. K . 1997. Physical model studies for riprap design of tow-induced forces. Report No. WES/TR/CHL-97-7. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Maynord, S. T. and T. S. Siemsen. 1990. Physical forces generated by barge-tow traffic within a navigable waterway. Pages 610-615 in Chang, H. H. and J. C. Hill, editors. Hydraulic engineering. American Society of Civil Engineers, New York.

Maynord, S. T. 2004. Ship effects at the bankline of navigation channels. Maritime Engineering 157:93-100.

Miranda, L. E. and K. J. Killgore. 2013. Entrainment of shovelnose sturgeon by towboat navigation in the Upper Mississippi River. Journal of Applied Ichthyology 29:316-322.

Okuyama, J., O. Abe, H. Nishizawa, M. Kobayashi, K. Yoseda, and N. Arai. 2009. Ontogeny of the dispersal migration of green turtle (*Chelonia mydas*) hatchlings. Journal of Experimental Marine Biology and Ecology 379:43-50.

Parker, A. D., P. B. Rogers, S. T. Finney, and R. L. Simmonds Jr. 2013. Preliminary results of fixed DIDSON evaluations at the electric dispersal barrier in the Chicago Sanitary and Ship Canal. U.S. Fish and Wildlife Service Interim Report, Carterville, IL.

Sass, G. G. and B. C. Ruebush. 2010. An *In-situ* Test of the Aquatic Nuisance Species Dispersal Barrier for Preventing Range Expansions of Small Fishes. Final Report on Supplemental Research Contract USEPA-GLNPO EPA GL 9655501

Sparks, R. E., T. L. Barkley, S. M. Creque, J. M. Dettmers, and K. M. Stainbrook. 2010. Evaluation of an electric fish dispersal barrier in the Chicago Sanitary and Ship Canal. Pages 139-161 in D. C. Chapman and M. H. Hoff, editors. Invasive Asian carps in North America. American Fisheries Society, Symposium 74, Bethesda, MA.

Taylor, D., K. Hall, and N. MacDonald. 2007. Investigations into ship induced hydrodynamics and scour in confined shipping channels. Journal of Coastal Research 50:491-496.

Witherington, B. E. 1995. Observation of hatchling loggerhead turtles during the first few days of the lost year(s). Pages 154-157 in J. I. Richardson and T. H. Richardson, editors, Proceedings of the 12th annual workshop on sea turtle biology and conservation, NOAA technical memo. NMFS-SEFSC-361.

Wolter, C. and R. Arlinghaus. 2003. Navigation impacts on freshwater fish assemblages: the ecological relevance of swimming performance. Reviews in Fish Biology and Fisheries 13:63-89.

Wolter, C. and R. Arlinghaus. 2004. A model of navigation-induced currents in inland waterways and implications for juvenile fish displacement. Environmental Management 34:656-668.