Summary of Fish-Barge Interaction Research and Fixed Dual Frequency Identification Sonar (DIDSON) Sampling at the Electric Dispersal Barrier in Chicago Sanitary and Ship Canal

Summary

As part of ongoing efforts to monitor the efficacy of the electric barriers, the U.S. Army Corps of Engineers (USACE) and the U.S. Fish and Wildlife Service (USFWS) have conducted laboratory and field experiments to assess the potential impacts of barge tows traversing the electric dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC) and the resulting impacts to fish behavior. The experiments consisted of the following:

- Development of a scale physical model to evaluate the possibility of fish being inadvertently transported across the electric barriers by navigation operations in the CSSC;
- Instrumented barge testing to determine the effects of loaded and unloaded barges traversing the barriers on electric field strength; and
- Observation of fish behavior during barge testing through the use of caged fish and tethered wild fish trials.

USFWS is also evaluating wild fish populations and their behavior within the electric dispersal barrier using a dual-frequency identification SONAR (DIDSON) unit to evaluate fish populations throughout the entire barrier system.

The preliminary findings of this research and proposed future actions are summarized in the following white paper. The information contained in the paper is based on preliminary results. Additional review and analysis, as well as additional testing will be required to fully understand the data and any potential impact on barrier operations and navigation within the CSSC.

Initial findings indicate that vessel-induced residual flows can trap fish and transport them beyond the electrical barriers, and that certain barge configurations may impact barrier electric field strength. Additionally, the preliminary DIDSON findings identified the potential for small fish (between 2-4 inches in length) to pass the barrier array in large groups, or schools.

There is no evidence that Asian carp are bypassing the barriers. Nor is there any indication that Asian carp are in the vicinity of the barriers. The closest adult Asian carp found in the Illinois River are about 55 miles from Lake Michigan, and no small Asian carp have been observed closer than 131 miles from Lake Michigan.

Future research will include a variety of simulations to further evaluate fish behavior, effects of the electrical field on groups of fish and how these may relate to operational protocols of the barriers and navigation within the CSSC. The research will be undertaken by the USACE Engineer Research and Development Center (ERDC) over a two year period, with priority placed on completing the studies of other fish, group challenges, and encroachment behaviors as soon as possible.

The Asian Carp Regional Coordinating Committee (ACRCC) will continue ongoing initiatives in the Chicago Area Waterway System (CAWS), which have been effective in controlling Asian carp. As part of these efforts, the USFWS will conduct more fixed DIDSON sampling in 2014. These samples will be taken in the summer or fall months when fish are known to be concentrated in the barrier area.

Introduction

The U.S. Army Corps of Engineers (USACE) and the U.S. Fish and Wildlife Service (USFWS) have conducted laboratory and field experiments to assess the potential impacts of barge tows traversing the electric dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC) and the resulting impacts to fish behavior. The experiments consisted of the following:

- Development of a scale physical model to evaluate the possibility of fish being inadvertently transported across the electric barriers by navigation operations in the CSSC;
- Instrumented barge testing to determine the effects of loaded and unloaded barges traversing the barriers on electric field strength; and
- Observation of fish behavior during barge testing through the use of caged fish and tethered wild fish trials.

USFWS is also evaluating wild fish populations and their behavior within the electric dispersal barrier using a DIDSON unit to evaluate fish populations throughout the entire barrier system, which covers the entire gradient of barrier voltages, and to perform concentrated evaluations directly over the strongest part of the barrier.

Briefly, preliminary findings indicate that 1) vessel-induced residual flows can trap model fish and transport them beyond the electrical barriers; 2) slow vessel speeds tend to transport model fish the farthest in the direction of the tow; 3) high vessel speeds produce the strongest reverse current, which transports model fish in the opposite direction of the vessel; and 4) the dominant transport mechanism in the direction of the tow movement is the recess formed in the rake between two barges. Proposed future actions include additional studies, conducted over a two-year period, to further evaluate operational protocols of the barriers and to identify any potential actions that may be employed.

The USFWS found that caged fish placed along the side and front of a barge vessel were all incapacitated. Caged fish that were placed in and around various barge junctions were incapacitated to varying degrees. Most of the fish that were within the rake-to-box junction wedge were not incapacitated. The use of uncaged fish in fish-barge interaction trials revealed that all barge configurations were capable of transporting live fish beyond the barrier to various degrees. Previous work with the DIDSON throughout the entire barrier system revealed that fish significantly accumulated below the active barrier and were sometimes observed persistently probing and challenging the barrier. When two fixed DIDSON units were deployed over the zone of ultimate field strength we were able to obtain 72 10-minute recordings of fish behavior. Of the 72 DIDSON samples taken, 44 of them (61%) revealed at least one school of fish passing through the barrier. Of those 44 samples with bypasses, 27 of those (61%) revealed multiple fish bypasses of the barrier.

I. Physical Model

The USACE Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) constructed a flume system (Figure 1) to model a scaled-down version of the CSSC electric dispersal barrier system. Model fish (Figure 2) were placed just below the barrier replicas and model barge tows were then driven through the barrier in various configurations. The size range of model fish sizes were chosen to best approximate the prototype fish interaction with different scales of water motion created by the tow. The model fish were modified to be as neutrally buoyant as possible with a buoyant condition preferred over a sinking condition. This was chosen on the observation that electrofishing is a common practice in capturing Asian carp. Additionally, fish near the surface will have greater interaction with navigation traffic, representing a worst case scenario. The model fish used cannot swim to evade the navigation traffic, removing behavioral patterns from the study. The study assumed the fish were stunned by the electric barrier, became incapacitated, and were passively transported with the current.

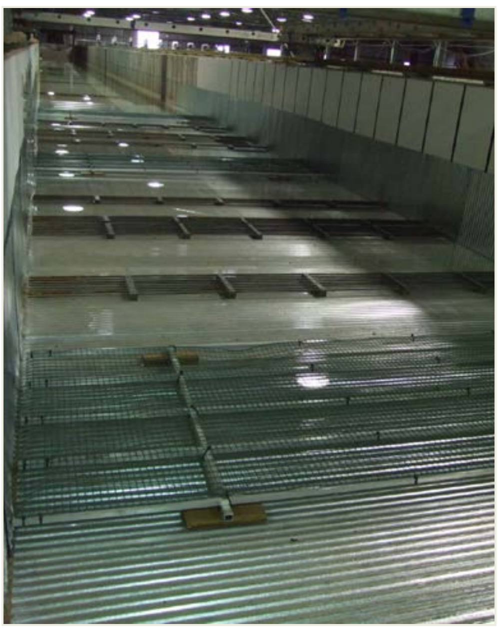

Figure 1. ERDC-CHL Flume

Figure 2. Model fish

Hydrodynamics around the tow were considered in the identification of different mechanisms that could transport fish. Vessel speed and tow/barge configuration are considered to be primary factors that affect the possible entrainment and transport of fish through the electric barriers. As an example, a tow traveling at the recommended no-wake speed of 4 miles per hour (mph) will traverse an entire barrier in only 22.2 seconds and the narrow array (highest voltage section of an electrical barrier) in 6 to 7 seconds. To evaluate the influence of these factors, ERDC-CHL identified a complex suite of water movements that barge tows create in confined channels such as the CSSC. These movements are depicted in Figure 3 and defined below. The barge configurations are shown in Figure 4.

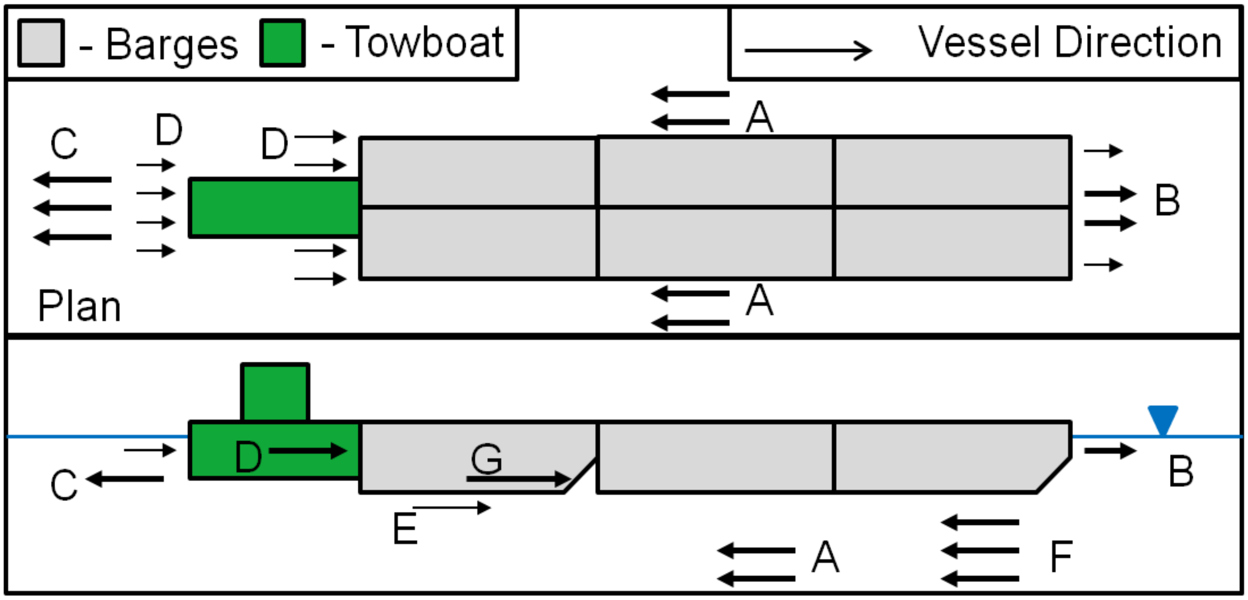

Figure 3. Water motions around tows moving left to right in confined channels. A = return velocity, B = bow wave, C = propeller jet, D = wake flow, E = flow in boundary layer along hull, F = displacement flow at bow between hull and channel bottom having short duration and G = pocket recirculation. Figure created by ERDC-CHL.

Return Velocity (A) – When a vessel moves through a waterway, the hull displaces water forcing the flow alongside and beneath the vessel opposite to the direction of the vessel. The flow moving opposite the direction of the vessel is referred to as return flow or return velocity. In a channel as small as the CSSC, return velocity tends to be relatively uniform over the entire cross section including the area beneath the hull of the tow. For downbound (southbound) tows, return velocity is opposite the ambient flow.

Bow Wave (B) - Directly ahead of the tow, the rectangular shape of the barge (plan view) creates a bow wave that sets water in motion in the same direction as the tow. If the channel is not too deep relative to the draft, and if the tow is traveling at high enough speed, the bow flow extends over the full depth but is significantly greater at the surface than at the bed. The bow flow is greater for square-end barges than the more streamlined raked barges.

Propeller Jet (C) - The propeller jet generates strong currents and turbulence resulting in a complex flow field behind the tow. At full speed the flow speed exiting the propellers can range up to 30 feet per second (fps) and extend over the depth of the water column. For lower speeds, typical of the CSSC, the propeller jet is much weaker and may not reach the bed. For these lower speeds, near-bed velocities under the propeller jet are dominated by the wake flow (D) and are in the same direction as the tow. For all propeller speeds, outside the width of the propeller jet but behind the barges, the wake flow is the dominant mechanism and the current is in the same direction as the tow.

Wake flow (D) - Directly behind the stern is the wake zone, where a reverse pressure gradient is produced causing the surface flow to move in the direction of the tow at about the same speed as the tow. The abrupt change in geometry between the last barge and the towboat likewise produces a barge wake zone and associated eddies that are carried along with the tow. For a typical two-wide barge configuration, the barge wake is symmetric on either side of the towboat. Debris and other particles can be trapped in the wake zones and carried for long distances.

Vessel Boundary Layer (E) – Moving vessels develop a turbulent boundary layer due to the no slip condition at the hull. The size and strength of this boundary layer depends on the vessel speed, hull roughness, channel geometry and the CSSC discharge. The no slip condition causes the current adjacent to the hull to move at the same speed and direction as the tow.

Displacement Velocity (F) - Displacement flow is only present beneath the bow of the barges and is relatively uniform over the distance between the hull and the bed.

Barge Junctions (G) - The junction of two raked barges or the junction of a square-end barge and a raked barge forms a protected area with weak, closed circulation. Water in these recesses may form an eddy that is similar in diameter to the barge draft. As with the wake flow, the exchange of water, debris, and fish in and out of this recess is controlled by the barge speed, local geometry, Reynolds number, and floating object characteristics.

With the exception of the return velocity (A) and propeller jet (C) these flows move in the direction of the tow. The return velocity and propeller jet pose a risk for fish transport past the barriers for southbound traffic, while the remaining modes of transport apply to northbound tows. Particles, such as the model fish used in this study, become trapped in these zones and are passively transported with the tow. Two aspects of model fish movement by these mechanisms is their likelihood of occurrence and the transport capacity. The return velocity acts over the entire cross section and every fish adjacent to or beneath the tow will feel its effect but the capacity to move the fish large distances is not great. Even though the probability for fish transport via the return velocity is high, they may or may not be moved through the electric barriers. For other mechanisms such as the pocket between barges (G) or the wake corners (D) at the towboat/barge junction, only some of the model fish enter these zones and the likelihood is less. However, the capacity of these modes to transport fish beyond the barrier is high. Once a model fish enters either a barge junction (G) or a wake corner (D), the distance the fish travels depends on the time required for the fish to get flushed from the eddy.

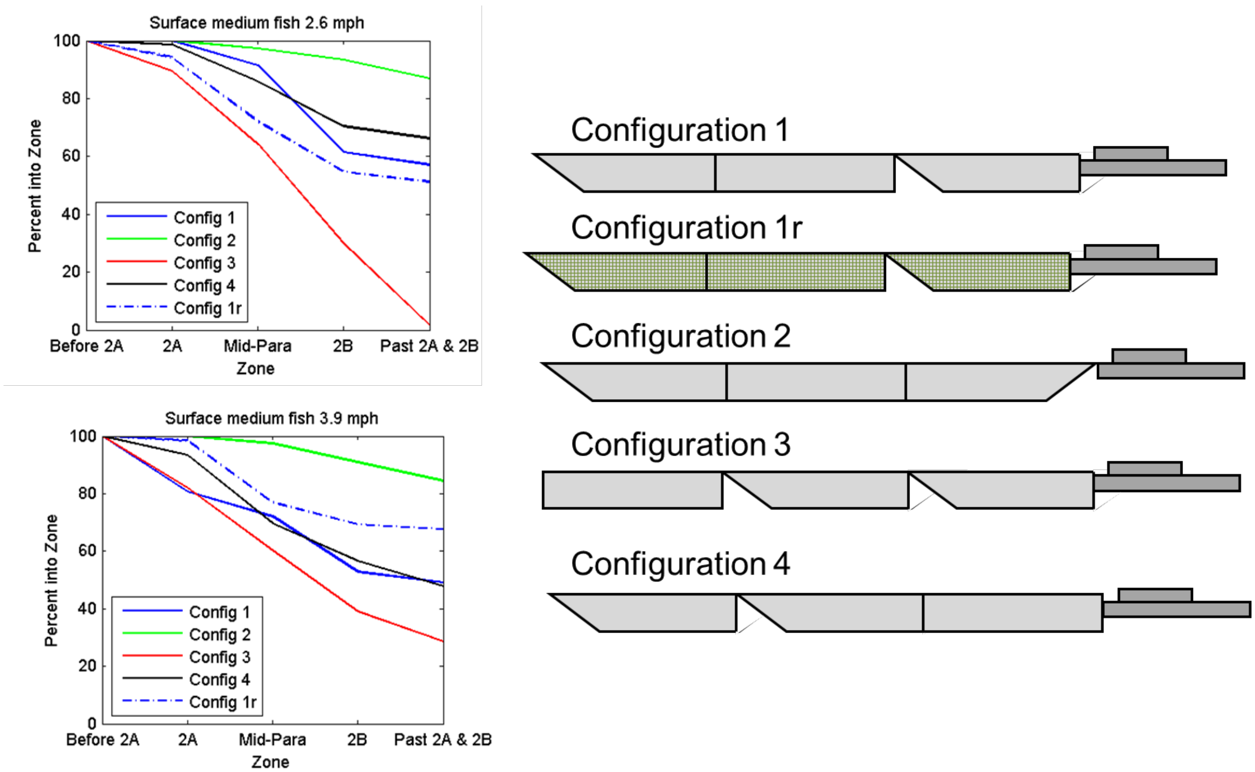

Figure 4. Percentages of model fish carried beyond the model Barrier IIA (2A), the middle parasitic structure (Mid-Para Zone), Barrier IIB (2B), and beyond all of the structures for both barriers (Past 2A & 2B). Note 1r utilized barges with "roughened" bottoms to more accurately represent barge tows transiting the electric barrier. Figure created by ERDC-CHL.

While all barge configurations entrained fish beyond the barriers in the model, researchers noted that some configurations entrained more fish than others. Configuration 2, in which the raked ends of the barges are at the front of the vessel and lashed to the tow, entrained the highest percentage of fish. Configuration 3, in which the square-barge ends were at the front, entrained the lowest percentage of fish.

ERDC-CHL also evaluated the relationship of tow speed to probability of entrainment. The research suggests that tows heading in the southbound direction, away from Lake Michigan, transport fewer fish when moving at slower speeds (e.g. around 2 mph or 2.9 fps) However, the effects of speed on transport of fish when the tow travels in the opposite direction (northbound, toward Lake Michigan) vary based on the barge configuration.

Further details and recommendations on these mechanisms of transport with regard to tow configuration, speed and tow position will be presented in a forthcoming data report once a comprehensive data analysis has been completed. Preliminary analyses of results indicate:

- Vessel-induced residual flows can trap model fish and transport them beyond the electrical barriers.
- Distance traveled depends on several factors, but slow vessel speeds tend to transport model fish the farthest in the direction of the tow. In contrast, the highest vessel speeds of 4 mph or 5.9 fps produce the strongest reverse current, which transports model fish in the opposite direction of the vessel.

- The dominant transport mechanism in the direction of the tow movement is the recess formed in the rake between two barges.

II. Instrumented Barge Testing

The ERDC Construction Engineer Research Laboratory (ERDC-CERL) outfitted barges with specially designed electrical probes to assess the effect that metal barge hulls have on the barriers' electrical fields as they move over the barriers. The barges were instrumented in a dry dock facility with several 3-dimensional voltage probe arrays in various locations. Each array contained three sensors spaced 1, 2, and 3 feet from the surface of the barges (Figures 5 and 6). A pair of arrays was suspended within the wedge of the rake barge to measure the electric fields within this area (Figure 7). The testing included measurement of the electric field strength at the voltage probes as the barges traversed the barriers. The barge tow configuration and the operating parameters of Barriers IIA and IIB were varied to simulate different operating scenarios.

Figure 5. 3 Dimensional probe arrays along the bottom edge of rake barge in dry dock.

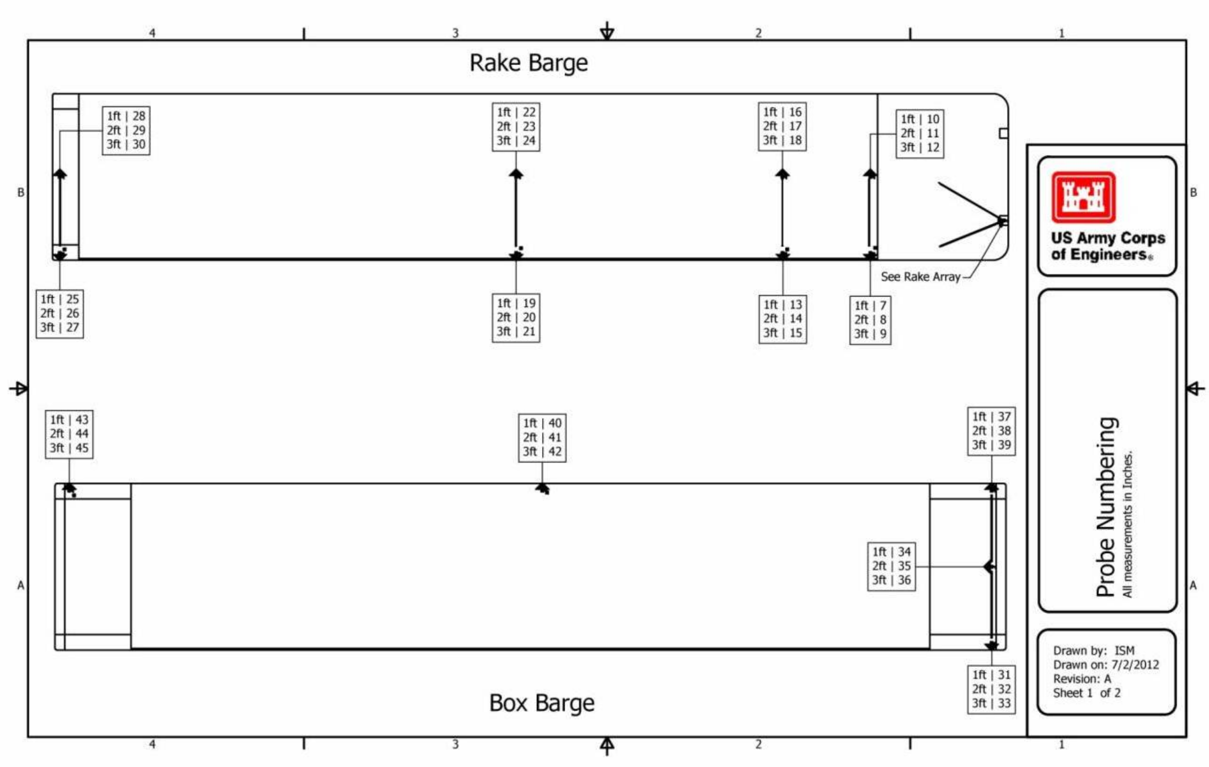

Figure 6. Sensor array locations and numbering for the rake and box barges.

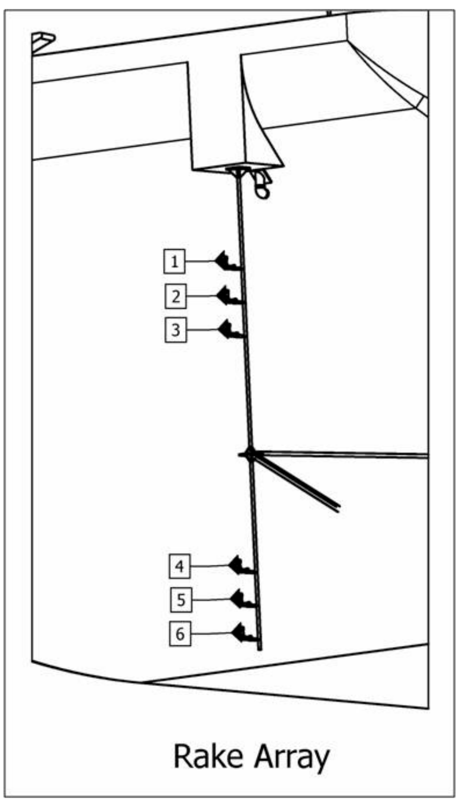

Figure 7. Rake array locations and numbering

During testing, electrical field data was collected on up to 24 channels per run at a sampling rate of 8000 samples per second. These readings were georeferenced using GPS receivers mounted to the forward and aft areas of the instrumented barge. The combined electrical and geo-positional data was used to determine the strength and direction of the electrical field around the barges throughout the barrier zone. Testing occurred with the barges in multiple configurations (Figure 8) to simulate tow configurations regularly utilized by shipping companies.

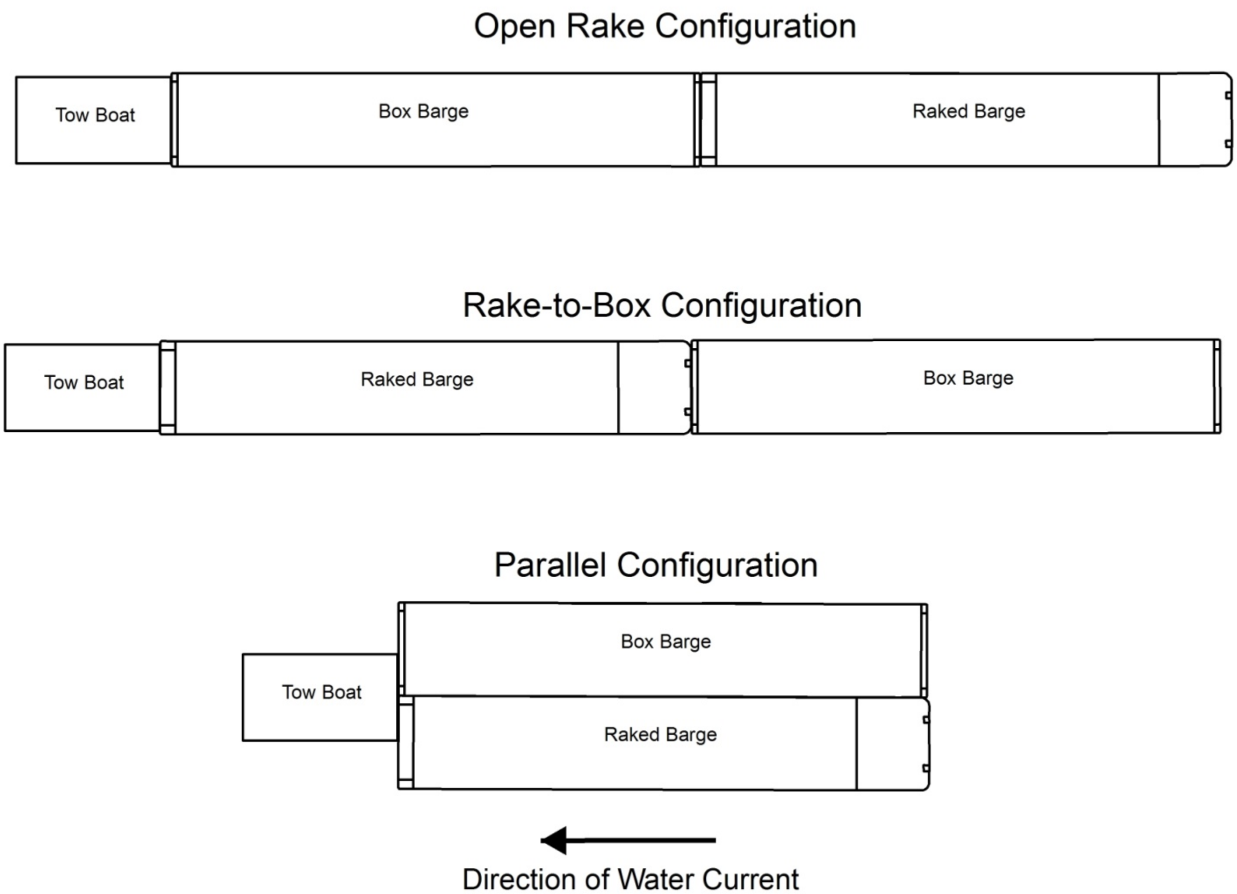

Figure 8. Barge Testing Configurations

Researchers recorded voltages that were strong enough to incapacitate fish alongside a barge and found elevated voltages at the front of the barge vessel as it traversed through the barrier (Figure 9). The preliminary data shows that the electric field produced by the barriers in the water is significantly altered by the presence of barges traversing the canal. This alteration is in both magnitude and direction and depends on the configuration of the barges. The key conclusions that can be drawn from the data at this time are:

- Sensors located along the bottom of the barges measured significantly higher voltage gradients than are measured during routine electric field mapping in a fiberglass hulled boat.

- Sensors located along the bottom of the barges measure a significant distortion in the direction of the electric field. Specifically, it appears that the dominant electric field direction is normal to the surface of the barges. This indicates that the barges are attracting the electric current from the water.
- In an open rake configuration, the electric field in the water beneath the rake is increased in magnitude.
- In a rake-to-box configuration, the electric field in the water beneath the rake is significantly reduced to the point that it is barely measureable.

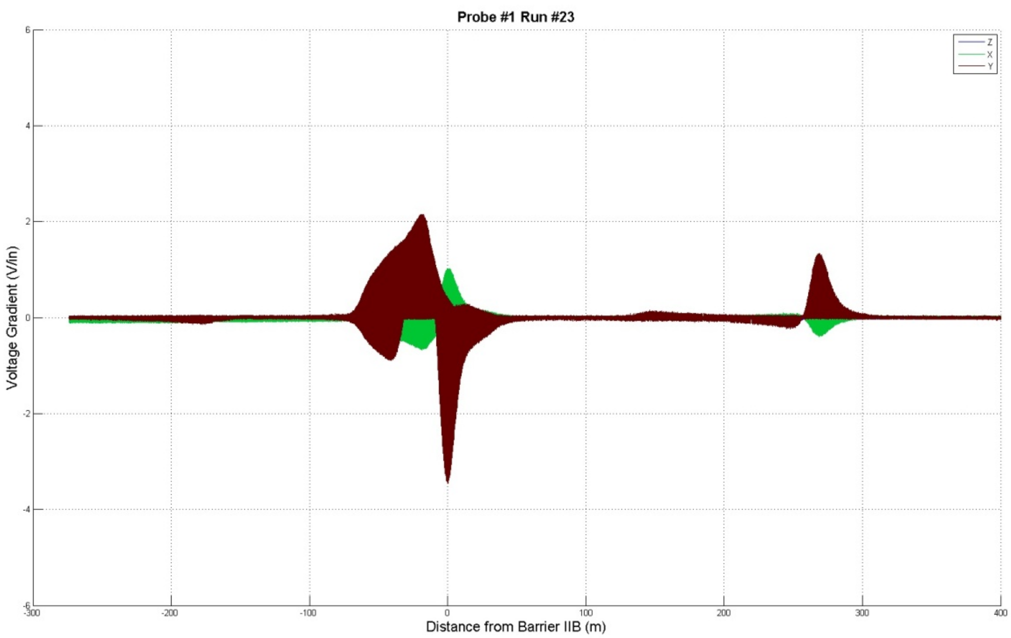

Figure 9. Field strength measurements over Barrier IIB and the Demonstration Barrier from Probe 1 in the open rake section of an instrumented barge. Barges passing over operating barriers IIB (centered at 0 on the x-axis) and the Demonstration Barrier (centered around approximately 270 m on the x-axis) show significantly amplified field strength near the surface of the water. With typical peaks of 2.3 Volts/inch and 1 Volts/inch when no barges are passing, the peaks measured from the rake section of a passing barge were 3.7 Volts/inch and 1.4 V/inch. Figure created by ERDC-CERL.

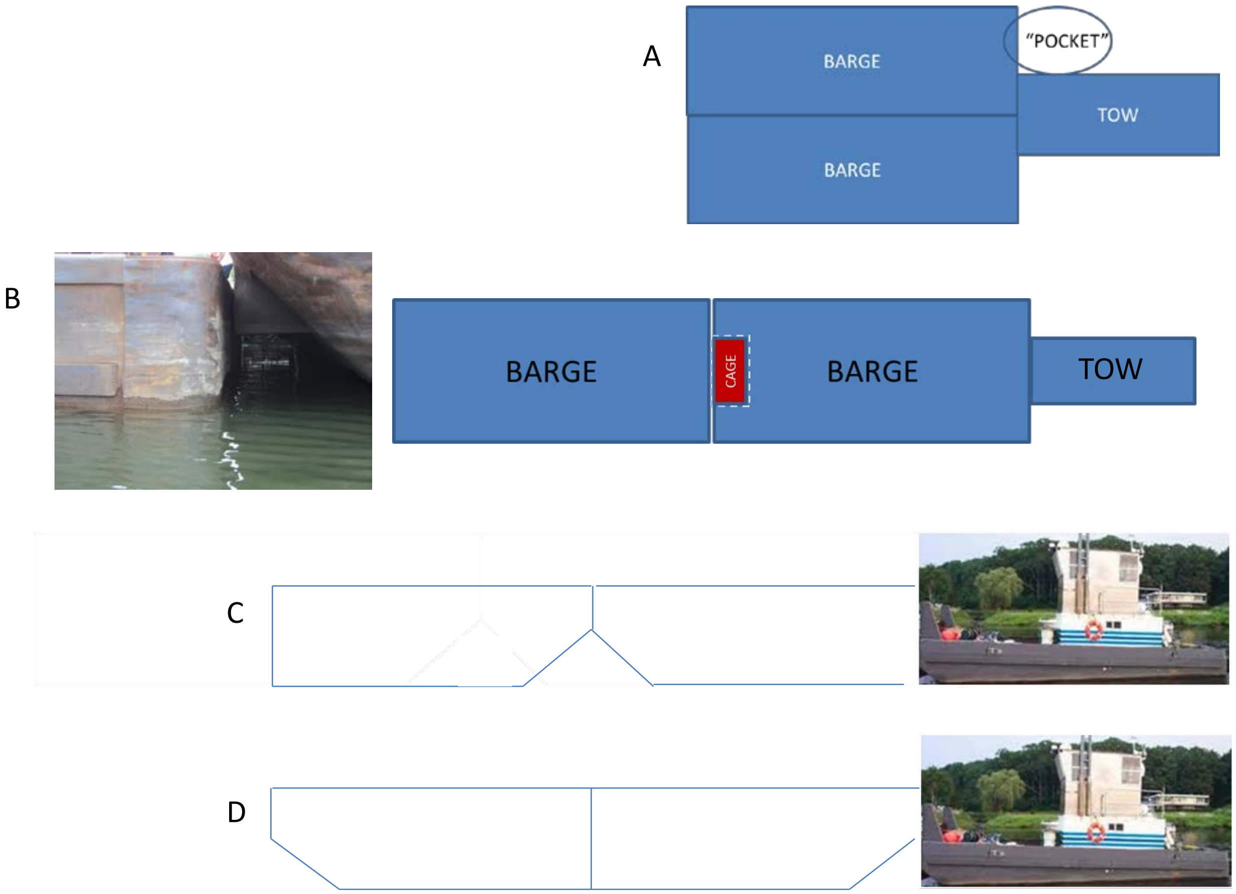

Figure 10. Schematics of four barge configurations used for voltage measurements at junctions and for fish interaction evaluations. A = Parallel barge configuration in which the tow boat is centered on the two barges. As the barges move forward a "pocket" eddy of water forms in the wake flow that can move debris forward with the barge. B = rake-to-box configuration. C = rake-to-rake configuration. D = rake-to-tow configuration.

III. <u>Fish-Barge Interaction</u>

The US Fish and Wildlife Service placed live surrogate species of fish in cages alongside and between junctions of barges in the CSSC to evaluate fish-barge interactions and assess the possibility of the fish becoming incapacitated as they traversed the electrical barrier. Fish that were used in the trials were primarily Gizzard Shad (*Dorosoma cepedianum*), but Common Carp (*Cyprinus carpio*) and Freshwater Drum (*Aplodinotus grunniens*) were used in some trials, depending on availability. Specifically, progressively larger fish were used 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. Gizzard Shad were chosen as a surrogate species because their body morphologies and habitat preferences are similar to those of Asian carp. Common Carp and Freshwater Drum were used as larger surrogate species because they were the most readily available large fish within the CSSC. Common Carp are considered to be a comparable surrogate to Asian carp, and the USACE-Chicago District is currently using Common Carp that are implanted with combined radio-and-acoustic transmitters to assess barrier efficacy. All fish were collected via electrofishing within the CSSC on the day that they were used in trials.

Caged fish placed along the side and in the front of a barge at the bow of the tow were incapacitated. Caged fish placed in the pocket eddy of a parallel configuration (Figure 10A) were incapacitated; however, there was a minimal amount of flow in the eddy, which raised concerns that stunned fish may still remain entrained in the eddy beyond the barrier. Also of concern were wild mosquitofish (not stocked by USFWS) entrained beyond the barrier in this eddy during the barge runs. Caged fish placed in the wedge of water between a rake-to-box junction (Figure 10B) were not incapacitated. Also of concern was a small wild fish (not stocked by USFWS) that was entrained beyond the barrier in this wedge of water during one run.

Caged fish were placed in the wedge of water between a rake-to-rake junction (Figure 10C), which caused the fish to be briefly incapacitated when they were directly over the strongest part of the barrier. ERDC-CERL researchers confirmed that when the fish were briefly incapacitated, there was a brief spike of in-water voltage as the cage was directly over the strongest part of the barrier. Caged fish were also placed in the wedge of water between a rake-to-tow vessel configuration (Figure 10D). All of the fish were incapacitated in that junction wedge. Of all of the junction wedges where in-water voltage was measured, the rake-to-tow wedge had the highest amount.

After the caged-fish work was completed, all work focused on the interaction of loose fish (fish tethered to a small bobber by 1-lb. dynema line) and barge tows as they traversed the barrier. Two different methodologies were employed using loose fish: one in which fish were directly placed into the wedges of water between the barge junctions as the barge tow was moving towards the barrier and one in which the fish were deployed into the canal below the active barrier and the barge tow then traversed the barrier. Figure 11 summarizes the percentages of live fish passing through the barrier via different barge configurations and deployment methodologies.

Depending on the fish deployment method used, the number of fish passes varied. Deploying fish directly into the rake to tow junction wedge yielded no fish passes. This was most likely because of the high amount of water movement between the two vessels. When the loose fish were placed in front of the rake-to-rake configuration barge tow, the least amount of fish passed through the barrier. When the barges were attached in a rake-to-rake junction, the square end of the lead barge was what the fish first encountered as the barge tow moved upstream. Most of the fish were displaced to the side of the barge tow before it moved to the barriers. The only fish that did become entrained beyond the barriers were two fish that swam into a small void space between the two square ends (Figure 12).

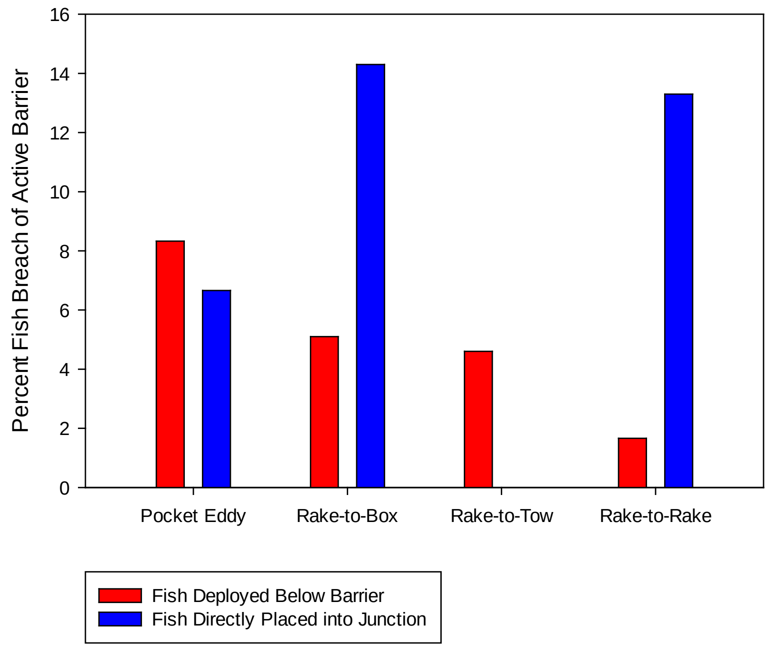

Figure 11. Percentages of live fish that passed through the barrier system via different barge junction configurations and fish deployment methodologies.

Figure 12. Picture of two barges traversing the electrical barrier with the square ends in the front of the barge configuration. The circle denotes the small void space that two live fish swam into and became entrained past the barrier.

Preliminary results of fish-barge interaction studies are:

- Fish in cages outside of the perimeter of the barges were incapacitated by the barrier when barges traversed.
- Fish in cages in void spaces ("wedges") in and around barges were not incapacitated or affected by the barrier, to varying degrees, depending on the location of the particular void space. Wild fish, not stocked by the USFWS, were observed passing through the barrier during these trials.
- Tethered fish placed in barge junctions passed through the barrier to some degree in all but one barge configuration tested. When tethered fish were placed below the barriers as barges approached, some degree of fish passage through the barrier occurred with every different configuration tested.

IV. Fixed DIDSON Fish Sampling

Results of sampling across the entire barrier system, using DIDSON equipment, revealed a large accumulation of fish below the active barrier. Some of the fish that were immediately below the active barrier (either Barrier IIA or IIB) were observed persistently probing and challenging the barrier. Observed fish behavior at two sites above the active barrier revealed mostly swimming and milling behavior. No probing or challenging behaviors (where by definition the fish's upstream movement is being slowed down or halted against an invisible plane) were recorded.

As part of the sampling regime in 2012, during the summer and fall, we also performed concentrated DIDSON sampling at the strongest part of the barrier. The concentrated sampling consisted of positioning a boat, with a single DIDSON unit deployed off of it, aimed at the western canal wall, ensonifying the water immediately below the surface. During the concentrated sampling, there were multiple incidences in which fish were observed swimming across the entire DIDSON viewing cone. However, no conclusions could be drawn as to whether actual passes of the barrier had occurred, in part, because a single DIDSON unit can only ensonify half the width of the narrow arrays. Further complicating the interpretation of the DIDSON footage between the narrow arrays was the movement of the boat (and subsequently the viewing cone) within the canal. Because of a concern that fish bypass of the barrier had occurred, the USFWS deployed two DIDSON units using a stable, fixed structure. The first sampling using two units over the narrow arrays occurred from July 30 to August 1, 2013.

The two DIDSON units were deployed from the west bank of the CSSC using a telescopic boom lift. The DIDSON units were deployed 10 meters (m) from the western canal wall, 1 m below the water surface, and were aimed towards the western wall. Both of the DIDSON units were simultaneously operated from one computer. 72- 10 minute recordings were captured. Out of the 72 recordings, 44 (61%) of them captured at least one occurrence of fish passing through the barrier. Of those 44 recordings which captured fish passage, 27 (61%) of those revealed multiple fish movements across the barrier. The sizes of the fish that passed through the barrier are estimated to range from approximately two to four inches in length. All of the fish observed passing through the barrier did so in schools. Typically, as the schools of fish penetrated deeper into the zone of ultimate field strength, the size of the school contracted into a tight sphere shape and after they passed through, the group expanded again. To help determine the species of fish most likely observed, the USFWS performed a limited amount of fish sampling within the narrow array on September 27, 2013 and caught Gizzard Shad (*Dorosoma cepedianum*), Threadfin Shad (*Dorosoma petenense*), and Skipjack Herring (*Alosa chrysochloris*).

Environmental data (dissolved oxygen [mg/l], pH, conductivity [µs/cm], and temperature [˚C]) were recorded once during each DIDSON recording interval at a fixed site immediately upstream of the barriers. Water velocity data for the times that DIDSON sampling took place were obtained from a U.S. Geologic Survey water gage located in the CSSC, 10.5 km upstream of the barrier safety zone (http://waterdata.usgs.gov/il/nwis/uv/?site_no=05536890). The environmental data collected during our sampling period revealed high temperatures and low flow velocities throughout the sampling period, although no reverse flows were recorded (Table 1).

Previous DIDSON sampling work found that fish were most abundant below the barrier and exhibited the most probing and challenging behavior when water temperatures were highest.

Date	Conductivity (mS/cm)	Dissolved oxygen (mg/L)	pH	Temperature (˚C)	Velocity (m/s)
7/30/2013	0.942 (0.004)	2.91 (0.028)	7.50 (0.091)	26.78 (0.168)	0.06 (0.008)
7/31/2013	0.962 (0.003)	3.13 (0.030)	7.58 (0.143)	22.78 (0.012)	0.19 (0.003)
8/1/2013	0.931 (0.002)	3.28 (0.020)	7.63 (0.040)	22.79 (0.020)	0.20 (0.010)

Table 1. Mean (± standard error) environmental data collected each day of DIDSON sampling.

V. <u>Future Actions</u>

Additional study is underway to further evaluate operational protocols of the barriers and to identify any potential actions that may be employed to address the findings discussed in this paper. The research, consisting of five tasks conducted in the ERDC, includes:

1. Simulations of a variety of fish behaviors during encroachment into the electric fields of Barriers IIA and IIB including extended stays in the low field (wide array) of the barriers, cross-channel swimming at the downstream edge of the high field (narrow array), and multiple challenges of the barriers;
2. Simulations of fish behavior at seasonal extremes of water temperature, water current velocity, and water conductivity;
3. Evaluation of the relationships between duration of electrical exposure and fish stress, injury, and mortality;
4. Evaluation of volitional challenges of electric fields by groups of fish; and
5. Simulations using other fish observed in the CSSC near the barriers, such as Gizzard Shad and Common Carp, to evaluate how similar their responses are to those of the Bighead and Silver carp.

These studies are scheduled to be completed over a two-year period, with priority placed on completing the studies of other fish, group challenges, and encroachment behaviors as soon as possible. Any sets of barrier operating parameters identified during these lab tests as potentially more effective than the current parameters will be deployed in field testing to further evaluate effectiveness and verify safety. If the field test results are also shown to reduce the risk of fish penetration of the barriers while maintaining safety requirements, the new parameters may become the full-time barrier operating parameters. Field testing of promising operating parameters will occur whenever warranted and can be done concurrent with completion of other laboratory tests.

Additionally, the USFWS will conduct more fixed DIDSON sampling in 2014. These samples will be taken in the summer or fall months when fish are known to be concentrated in the barrier area. Data will then be compiled for further analyses and shared with partners in order to have a better understanding of how resident fish within the CSSC are currently interacting with the electric barrier.