Fish Behavior and Abundance at the Electric Dispersal Barrier in the Chicago Sanitary and Shipping Canal at Reduced and Current Voltage Operating Parameters

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Great Lakes-Big Rivers Region
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Executive Summary

The Chicago Area Waterway System is an artificial network of heavily modified rivers and canals that connect the Great Lakes and Mississippi River Basins. Because of concern about inter-basin fish species exchange, an electric barrier is currently operated by the U.S. Army Corps of Engineers in the Chicago Sanitary and Ship Canal 60 km south of Lake Michigan. The electric barrier consists of two large barriers (only one of which was operated at any given time during the study period) and a smaller Demonstration Barrier. The larger barrier operated at 6.5 ms, 15 Hz, 0.79 V/cm (0.79 V/cm) from 8/2009 to 11/2011 before being increased to 2.5 ms, 30 Hz, 0.91 V/cm (0.91 V/cm). These operating parameters were configured to inhibit the upstream dispersal of Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*) from the Mississippi River Basin to Lake Michigan. The U.S. Fish and Wildlife Service (Service) - Carterville Fish and Wildlife Conservation Office began evaluating fish behavior at the electric barrier in 6/2011 when the barrier was operating at 0.79 V/cm and continued to this work after operating parameters were increased to 0.91 V/cm in 11/2011.

The Service’s efforts at the electric barrier consisted of a two-part study that involved observations of wild fish within the electric barrier and caged-fish behavioral trials at the barrier. The abundances and behaviors of wild fish were evaluated near the electric barrier using a dual-frequency identification SONAR (DIDSON) unit throughout the electric barrier. During the fall of 2011, when the barrier was operating at 0.79 V/cm, fish accumulated below the electric barrier and sometimes persistently challenged the electric field. Smaller fish were able to swim further into the electrical field, than larger fish, to the area of water containing the ultimate field strength. Caged-fish trials consisted of placing Gizzard Shad (*Dorosoma cepedianum*) in a non-
conductive cage that was attached to a boat and pulling the cage through the barrier. Eight of 270 fish that were pulled through the electric barrier did not become incapacitated.

After the barrier operating parameters were increased to 0.91 V/cm, we continued to evaluate wild fish behavior within and around the barriers and continued our caged-fish work throughout 2012. We found that wild fish at the electric barrier were scarce during the winter and spring, and were not observed near the areas of highest voltage. However, wild fish accumulated below the electric barrier the most during the summer and fall, and persistently challenged the barrier. Fish that were able to penetrate the farthest into the electric barrier were smaller and tended to aggregate at the water surface, near the canal walls.

Concentrated DIDSON sampling, in which all observations were made within the zone of ultimate barrier field strength, revealed schools of wild fish persistently probing the barrier. Fish were most abundant in this zone during the summer when both temperatures and dissolved oxygen concentrations were high.

All caged-fish that were pulled through the barrier were incapacitated at some point with the increased operating parameters of 0.91 V/cm. However, the distance that the fish were able to swim varied considerably depending on season, size of fish, and the conductance of the boat that they were moved next to (aluminum or fiberglass hull). Fish that were moved through the barrier during the winter and spring seasons became incapacitated the soonest. The winter fish most likely became incapacitated after a short distance because of reduced metabolic function in the cold temperatures. The fish used in the spring were the largest fish used in the caged-fish trials because only age-1, wild Gizzard Shad were available at the time, and were incapacitated at the same distances into the barrier as the winter fish. When fish were moved through the barrier immediately adjacent to the canal wall, incapacitations were delayed, indicating that the canal wall
may weaken or distort the electrical field to some degree. The fish that were moved through the barrier in the summer showed the largest discrepancy in distances that they were able to swim into the barrier, depending on the type of boat used to move them. Fish that were moved along an aluminum-hull boat were able to swim nearly twice the distance into the barrier before becoming incapacitated, as those that were moved along a fiberglass-hull boat. The delayed incapacitations of fish moving along the aluminum-hull boat are presumably due to electrical distortion caused by the metal boat conducting electricity. These results raise concerns about the effect that the numerous metal-hull barges have on the barrier as they traverse it and the potential for them to facilitate fish breach. The accumulation of fish that were observed below the barrier, and the persistent challenging, also raises concerns about barrier breaches any time the barrier must be de-energized for maintenance, and when barge vessels traverse the barrier.


Introduction

The Laurentian Great Lakes Basin has a long history of exotic species introductions (Mills et al. 1993; Holeck et al. 2004). The Mississippi River Basin contains fewer invasive species than the Great Lakes, however, it does have established populations of Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*). These two species are of particular concern because of their rapid population growth and planktivorous feeding ecology, which may compete with native larval fishes and adult filter-feeding fish (Chick and Pegg 2001; Schrank et al. 2003; Irons et al. 2007; Cooke and Hill 2010). Linking the Great Lakes and Mississippi River Basins, and potentially serving as a conduit for inter-basin, invasive species exchange is the Chicago Area Waterways System (CAWS).

The CAWS is a system of man-made canals and heavily modified rivers that now permanently link the Great Lakes and Mississippi River Basins (Fig. 1). In 1910, upon completion of the Chicago Sanitary and Ship Canal (CSSC), water flow in the Chicago River and the North Shore Channel were permanently reversed, with water flowing from Lake Michigan to the Mississippi River Basin. This was done mainly for the purpose of diverting sewage away from Lake Michigan, which is the source of drinking water for the city of Chicago, Illinois. Soon after the completion of the CSSC, the Calumet-Saganashkee Channel (Cal-Sag Channel) was connected to the CSSC, which reversed water flow from the Calumet, Grand Calumet, and Little Calumet Rivers towards the Mississippi River Basin (Cain 1978; Moy et al. 2011).
Initially after the flow reversal, the amount of waste load from municipal and industrial sources created a hypoxic zone that began in the CSSC, continued into the Des Plaines River, and into the upper Illinois River. This “pollution barrier” rendered those systems devoid of fish and prevented any inter-basin species exchange (Mills et al. 1966). Starting in the 1970’s, water quality improved as a result of the Clean Water Act, enough so that fish began to inhabit the CSSC (Moy et al. 2011). Today, approximately 70 different fish species occur in the CAWS (Kevin Irons, Illinois DNR; personal communication). The water quality improvements have also allowed invasive species such as zebra mussels (*Dreissena polymorpha*), White Perch (*Morone americana*), and Round Goby (*Neogobius melanostomus*), which had originally invaded the
Great Lakes, to expand their ranges into the CAWS and Illinois River (Stoeckel et al. 1996; Steingraeber and Thiel 2000; Rasmussen 2002; Irons et al. 2002; 2006). Other potentially harmful, non-native species such as Alewife (Alosa psuedoharengus), Oriental Weatherfish (Misgurnus anguillicaudatus), and Sea Lamprey (Petromyzon marinus) have been documented in the CAWS (Retzer and Batten 2005).

In 1990, the U.S. Congress authorized the U.S. Army Corps of Engineers (USACE) to study non-physical barriers in the CAWS in an effort to prevent the invasion of Round Goby into the Mississippi Basin (Sparks et al. 2010). A group of scientists and managers formed the Dispersal Barrier Advisory Panel in 1996 and were tasked with considering various, non-physical, fish dispersal barriers. Based on several factors such as cost, success likelihood, amount of environmental impact, commercial availability, permit requirements, and effects on existing uses of the CAWS, an electrical barrier was recommended as the best option for a non-physical fish barrier (Moy et al. 2011).

The use of electricity to divert or prevent fish movement has origins in the early 20th century with some of the first experiments taking place in the 1920s and 30s (McMillan 1928; Hartley and Simpson 1967). Early electrical fish barriers consisted of metal electrodes spanning the entire vertical water column of rivers, thus impeding fish movement via electrical repulsion, but also creating physical barriers (McLain 1957; Hartley and Simpson 1967). In rivers where physical obstructions are undesirable, bottom-mounted electrode arrays have become more common (Swink 1999; Moy et al. 2011). The effectiveness of electrical fish barriers have been evaluated in controlled laboratory and field settings (Barwick and Miller 1996; Savino et al. 2001; Dawson et al 2006; Holliman 2011) and at permanent barrier locations in small streams and canals (Swink 1999; Verrill and Berry 1995; Maceina et al. 1999; Clarkson 2004). Effectiveness of
electrical barriers in controlled laboratory settings were evaluated via direct observation. Studies in field settings relied on indirect assessment methods such as mark-recapture, and tagging, as well as sampling above the barrier for the targeted species. Although the barriers in the above-mentioned studies were largely effective, only Maceina (et al. 1999) found their electric barrier to be 100% effective at inhibiting the movement of the targeted fish. Causes of barrier breach in other studies included persistent challenging of the barrier by the fish (Barwick and Miller 1996; Savino et al. 2001; Dawson et al. 2006; Holliman 2011), increased water flows (Verrill and Berry 1995), or unknown causes (Swink 1999). Clarkson (2004) extensively documented numerous problems that arose at a barrier in an Arizona canal, mainly power outages, that resulted in grass carp (*Ctenopharyngodon idella*) breach of the barrier.

In April 2002, an electric Demonstration Barrier was activated in the CSSC, however, this was too late to stop the downstream dispersal of Round Goby, which were first found within the Mississippi drainage in 1996 (Steingraeber and Thiel 2000; Sparks et al. 2010). This electrical barrier is much different than any other past or present electrical barriers in several respects. The section of the CSSC where the barriers are located, near Romeoville, Illinois, is 57-m wide and 7.7-m deep making this electric barrier much larger than any other previous examples; flow and conductivity vary greatly, and the canal is actively used for commercial and recreational vessel navigation (Moy et al. 2010; Sparks et al. 2010).

Sparks et al. (2010) and Dettmers et al. (2005) were the first to directly test the effectiveness of the Demonstration Barrier, which originally operated at 2 ms, 2Hz, < 0.39 V/cm (Holliman 2011). Sparks et al. (2010) released 130 Common Carp (*Cyprinus carpio*) with surgically-implanted, combined radio-and-acoustic transmitters downstream of the barrier. Movements were recorded from 2002 to 2006 and during that time one fish was able to breach the barrier on
April 3, 2003. This breach was later determined to have coincided with the passage of a barge through the barrier, after a review of barrier electrical data, which shows distortions caused by barges. This breach 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 (Sparks et al. 2010). After the fish moved upstream of the barrier, it ceased moving, indicating that the fish was either dead when it breached, or died shortly after breaching. Despite uncertainty as to how the fish breached, the barrier electrical parameters were increased to 5 ms, 3 Hz, < 0.39 V/cm, and later to 4 ms, 5 Hz, 0.39 V/cm in response to the fish passage upstream (Holliman 2011). The Demonstration Barrier continues to operate today, but at a reduced capacity of about 0.31 V/cm because of its age (McInerney et al. 2011).

During November 2003, Dettmers et al. (2005) passed encaged fish alongside a barge through the Demonstration Barrier. Fish used were Catastomidae species, Morone species, and Common Carp ranging in size from 170 – 580 mm TL. Dettmers et al. (2005) found that fish took longer to show signs of affectedness from the barrier moving downstream than upstream through the barrier. The effects of the electrical field were also delayed when fish swam alongside conductive (steel) barge hulls compared to non-conductive (fiberglass) hulls. Some fish that were towed along the steel-hulled barges were never incapacitated as they swam through the barrier. Dettmers et al. (2005) attributed the delayed and non-incapacitations to a distortion of the electrical field by the barges, which caused the field to warp towards the forward part of the barge and created electrical voids immediately alongside and to the rear of the barge.

Following the Dettmers et al. (2005) study, design modifications were made to two larger, additional electrical barriers, Barriers IIA and IIB, to account for the barge-induced electrical
warping. Barriers IIA and IIB were implemented in 2009 and 2011 respectively. The newer barriers cover a much larger area than the Demonstration Barrier and are capable of generating electrical fields of much higher intensity. These larger barriers also have parasitic structures, composed of woven cable wire, placed upstream and downstream of them to prevent stray voltage from reaching beyond the barrier “safety zone” (an area defined by the U.S. Coast Guard-Lake Michigan Sector encompassing all of the barrier structures between river km 476.5 and 477.5 of the CSSC). The two barriers consist of two downstream wide arrays that emit a weak electrical field and two upstream narrow arrays that emit the maximum target voltage (Fig. 2; Holliman 2011). The purpose of this gradual increase in electrical intensity, moving from downstream to upstream, is for fish to feel an increasingly unpleasant sensation, causing them to slow their swimming speed and eventually stop. Otherwise, if fish abruptly encounter a narrow, high electrical field, this may cause a panic response, in which the fish may continue to swim further into the barrier until it breaches the barrier under its own momentum (Hartley and Simpson 1967). Non-electrified spaces between the arrays were implemented with the intention of allowing fish that are attempting to swim along a barge to move away from the barge in those areas (Moy et al. 2011).

After the completion of Barrier IIA in 2009, additional field testing was performed by Sass and Ruebush (2010) and intensive laboratory work was performed by Holliman (2011) to find the most effective barrier operating parameters. The main focus of this work was preventing the upstream dispersal of Silver and Bighead Carp through the CSSC. Sass and Ruebush (2010) tested the effectiveness of the Demonstration Barrier and Barrier IIA when both were operating at 0.39 V/cm. Bluegill (*Lepomis macrochirus*), Common Carp, Golden Shiner (*Notemigonus crysoleucas*), Green Sunfish (*Lepomis cyanellus*), *Lepomis* hybrids, Largemouth Bass (*Microp-
terus salmoides), Orangespotted Sunfish (Lepomis humilis), Pumpkinseed (Lepomis gibbosus), and White Sucker (Catostomus commersoni) ranging in size from 66 – 262 mm TL were attached to tethers with floats, placed directly in the barriers, and responses to the barrier were directly observed and recorded. Only 3 out of 11 fish placed in the barriers operating at 0.39 V/cm were incapacitated. However, later when the operating parameters of Barrier IIA were increased to 6.5 ms, 15 Hz, 0.79 V/cm (0.79 V/cm), all 20 fish placed in the barrier were incapacitated.

Sass and Ruebush (2010) noted that smaller fish took longer to become incapacitated.

The operating parameters of Barrier IIA were increased to 0.79 V/cm in August 2009 as a result of a pilot laboratory study performed by Holliman (2011). Using Silver Carp ranging in size from 137-280 mm TL, Holliman (2011) found that at 0.79 V/cm, 100% of Silver Carp specimens were incapacitated. Barrier IIB began operation in April 2011 at 0.79 V/cm. At the time of our study, only one barrier (typically Barrier IIB) operated at a time along with the Demonstration Barrier (as of this writing both Barriers IIA and IIB concurrently operate along with the Demonstration Barrier). Barrier IIB operated at 0.79 V/cm until November 2011, when parameters were increased to 2.5 ms, 30 Hz, 0.91 V/cm (0.91 V/cm), which are the current operating parameters as of this writing. The increase to 0.91 V/cm was in response to additional intensive laboratory work done by Holliman (2011) on Bighead Carp that were 46-72 mm TL. Holliman (2011) found that those parameters incapacitated 100% of small Bighead Carp that were exposed to gradual increases in voltage in a Brett swim tunnel. However, those parameters were only about 90% effective at preventing fish from swimming through an electrical barrier, set at the current operating parameters of 0.91 V/cm, in a flowing runway that small Bighead Carp (48 – 82 mm TL) were allowed to challenge.
Given this history of studies that indicate potential entrainment of fish at the barrier was an issue, Carterville FWCO undertook these studies to further understand potential issues with entrainment at the barrier system under environmental conditions.

The behavior and abundances of wild fish that were present near the electric dispersal barrier in the CSSC were recorded as well as the behavior of caged fish that were moved through the barrier as part of this study. The behavior of specific fishes of interest that encounter electrical barriers has been described in both laboratory (McMillan 1928; Hadderingh and Jansen 1990; Savino et al. 2001; Dawson et al. 2006; Holliman 2011) and controlled field settings (Stewart 1981). Numerous studies exist on the use of electric barriers that are meant to divert fish away from an undesirable area, such as a power plant intake (e.g. Taft 2000). However, to the best of our knowledge, we are not aware of any other research that has focused on the behavior of established, wild fish populations that encounter a permanent fish barrier designed to completely stop upstream movements of fish. Godlewska et al. (2007) evaluated the abundances of wild fish in front of an electric barrier using hydroacoustics, however, fish were recorded as “still” images, and behavior could not be directly observed. We used a SONAR technology (described in detail below) that was capable of recording target movements with video quality, and therefore recorded the fish’s interactions with the electric barrier. By using this technology we were able to easily quantify the interactions of both individual and schooled fish with the barrier. We also sampled the electric barrier over a large area, from non-electrified water to the strongest part of the barrier, throughout an entire year. The use of caged fish that are moved through an electrical barrier is still a novel, experimental approach and the only other researchers to employ this method, that we are aware of, were Dettmers et al. (2005) on the Demonstration Barrier within the CSSC.
Field work at the larger barriers (IIA and IIB) was performed in June 2011 and continued after operating parameters were increased later that year. Because of the change in operating parameters in November 2011 to 0.91 V/cm, results from June to November 2011 are reported separately (when operating parameters were at 0.79 and 0.91 V/cm). Specific objectives at the previous operating parameters were to 1) describe the behavior of fish within various parts of the electric barrier, 2) determine the abundances of fish within various parts of the electric barrier, and 3) describe the behavior of encaged fish that are pulled through the barriers. Additional objectives after the current barrier operating parameters were initiated were to: 1) Determine the number of fish interacting with the barrier at the peak voltage area, and 2) continue to describe the behavior of encaged fish that are moved through the barriers. Initial caged-fish work consisted solely of using aluminum-hull boats. However, later fiberglass-hull boats were also used in order to contrast the effects that the metal-hull boat had on the barrier’s electrical field and whether fish behavior was affected by any potential field distortion.

In addition to caged-fish trials at the electric barrier, on June 12, 2012, caged-fish trials were performed within the Demonstration Barrier. These additional studies were performed after a brief barrier outage in May 2012 raised concerns about how large fish interact with the Demonstration Barrier after breaching the primary barrier.
Materials and Methods

Fish behavior and abundance near the barriers

Fish abundances and behaviors within the electric barrier were evaluated using dual-frequency identification sonar (DIDSON; Sound Metrics Corp., Bellevue, WA). The use of DIDSON by fishery scientists to obtain size, behavior, and abundance data is becoming increasingly common (Holmes et al. 2006; Boswell et al. 2008; Burwen et al. 2010; Becker et al. 2011). A DIDSON has two available frequency modes: a low frequency of 1.0 MHz, which has a maximum viewing range of 40 m, but a lower target resolution, and a high frequency of 1.8 MHz that has a lower viewing range of 12 m, but higher target resolution. The DIDSON software can process up to seven frames per second, so rather than an acoustic “still” image, DIDSON provides, near-video-quality, real-time imaging (Moursund et al. 2003). A DIDSON device is capable of capturing consistent images regardless of turbidity and light levels (Moursund et al. 2003), giving this technology advantages to traditional underwater video camera viewing (Stoner 2004; Mueller et al. 2006). A DIDSON is also capable of simultaneously imaging substrate, habitat features, and fish within the same pulses. This makes images much more interpretable than other SONAR methods (Boswell et al. 2008), especially when there is an interest in relating fish abundance and behavior to habitat features.

DIDSON footage was recorded at eight separate sites (Fig. 2; Table 1) with ten cross-channel sub-sites within each site (Fig. 3) for a total of 80 unique recordings during a sampling period (see Table 1 for description of sites). The sites were chosen to represent the entire gradient of voltage along the electric barrier. In-water voltages begin to rise at the downstream parasitic structure (site 2) and gradually rise until it peaks between the two narrow, high-field arrays.
(site 6). The voltage then abruptly decreases at the upstream parasitic structure (site 7; Fig. 2 [for
detailed maps of voltages throughout the electric barrier see McInerney et al. (2011)]).

Ten-minute recordings were made at each sub-site. The order in which to sample the sub-
sites was randomized with a random number generator. The DIDSON was operated in high-
frequency mode with a window length of 10 m starting 1.67 m in front of the transducer at a
frame rate of seven frames per second. The DIDSON unit was mounted to a heavy-duty pan and
tilt unit (Remote Ocean Systems, San Diego, CA) that was attached to a vertical metal pole. The
vertical pole was clamped onto a custom stanchion mount that was bolted to the gunwale of a
boat (Deep Development Corp., Sumas, WA). The DIDSON unit was deployed 1 m below the
water surface. The DIDSON unit was tilted at 0° for sub-sites A and J (in this case the 0° starting
orientation was considered to be when the DIDSON unit was parallel to the water surface), -25°
for B and I, and -45° for C-H (Fig. 3). Environmental data (water velocity [m/s], dissolved oxy-
gen [mg/l], pH, conductivity [µs/cm], and temperature [˚C]) were recorded once during each re-
cording when the DIDSON sampled a site (roughly every ten minutes). These data were collect-
ed at a fixed area downstream of the barriers. Sampling took place continuously during daylight
hours with the only interruptions occurring when a vessel passed through the barrier. No record-
ings were made during vessel passages and we waited several minutes to resume sampling after a
vessel passage.
Figure 2. Schematic of the electric barrier within the CSSC where DIDSON images were recorded. Note: drawing is not to scale and represents DIDSON recordings taken if Barrier IIB was operating. Sites were adjusted accordingly when Barrier IIA was in operation.
**Figure 3.** Cross-sectional illustration of the CSSC displaying ten sub-sites (A-J) across the canal where DIDSON footage was recorded within sites 1-8 from a north-oriented boat. Note: only one boat was used at a time to record one sub-site.

**Table 1.** Description of DIDSON recording sites.

<table>
<thead>
<tr>
<th>Site Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>Area downstream of all electrical structures where water-borne electricity is typically minimal.</td>
</tr>
<tr>
<td>Site 2</td>
<td>Area immediately downstream of the first operating parasitic structure where water-borne electricity is typically minimal.</td>
</tr>
<tr>
<td>Site 3</td>
<td>Middle of first operating, downstream parasitic structure.</td>
</tr>
<tr>
<td>Site 4</td>
<td>Area immediately downstream of the first operating wide-array, low-field structure.</td>
</tr>
<tr>
<td>Site 5</td>
<td>Area immediately downstream of the second electrode bank of the wide-array structure.</td>
</tr>
<tr>
<td>Site 6</td>
<td>Area between the two narrow, high-field arrays where voltage is typically highest.</td>
</tr>
<tr>
<td>Site 7</td>
<td>Middle of first operating, upstream parasitic structure.</td>
</tr>
<tr>
<td>Site 8</td>
<td>Area upstream of all barrier structures where voltage is typically minimal.</td>
</tr>
</tbody>
</table>

After collection, DIDSON footage was reviewed in the laboratory. Two reviewers examined the footage simultaneously and were allowed to slow down, pause, and rewind footage in order to best process all data. Individual fish (defined as a singular fish within the DIDSON viewing cone that was not swimming in a similar manner as any nearby fish) were treated differently from schools/shoals of fish (defined as two or more fish swimming similarly nearby each other and referred to as schools hereafter). Data were recorded separately for individual and schooled fish based on the results of Holliman (2011) who found that small Bighead Carp did not act independently when challenging an electrical barrier in a laboratory setting. Fish used by
Holliman (2011) would often approach and challenge the barrier in pairs or as a group, or fish would follow others into the electrical field.

Individual fish were measured with the DIDSON software measurement tool (cm) and behaviors were recorded. Four different fish behaviors were recorded: “swimming,” “flight,” “hovering,” and “probing.” “Swimming” was defined as steady, continuous movement by the fish in one general direction. “Flight” was defined as a noticeable deviation from normal swimming behavior including bursts of speed or rapid, erratic changes in direction. “Hovering” was defined as fish maintaining position in one spot for at least five seconds. “Probing” was defined as direct and persistent back and forth and/or up and down movement where forward progress seemed to be inhibited along an invisible plane. All observed behaviors were recorded for an individual fish or schools of fish. For example, if a fish showed hovering behavior and then probing behavior, both were recorded. When schools of fish came into the DIDSON view, the lengths of five randomly selected fish were recorded and averaged. The same behavioral data that were recorded for individual fish were also recorded for schools. Each fish that entered the DIDSON viewing area was treated as a separate fish. Therefore, the possibility exists that if an individual fish or school of fish was swimming back and forth through the DIDSON viewing area that those fish would be counted multiple times. Thus, fish abundance estimates may be elevated at all sites.

Only one season’s worth of DIDSON footage was recorded, using the standard method of sampling 80 different subsites, when the barrier was operating at 0.79 V/cm. Two separate methods of recording fish using the DIDSON unit were employed throughout 2012 after the barrier operating parameters were increased to 0.91 V/cm. One which evaluated fish behavior and abundance throughout the entire electric barrier, throughout the year (standard sampling; described
above) and another which focused on fish abundance and behavior within the zone of ultimate field strength (concentrated sampling; Site 6 in Fig. 2). The concentrated DIDSON footage focused on the western wall of the canal within the zone of ultimate field strength. In the standard sampling method, this area would be referred to as Site 6, Section A (Figs. 2 and 3). This site was chosen for concentrated evaluation because earlier work at the previous operating parameters had revealed that wild fish had been present at that location and interacted with the barrier mostly at the water surface, near the canal wall. Environmental data (dissolved oxygen [mg/l], pH, conductivity [µs/cm], and temperature [°C]) were recorded once during each DIDSON recording interval (during both standard and concentrated methods) at a fixed site downstream 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).

**Caged-fish trials**

Gizzard Shad (*Dorosoma cepedianum*) was used as a surrogate species to emulate small Asian carp attempting to traverse the barrier. Asian carp were not used in the caged-fish trials because of escapement concerns. The gizzard shad was chosen as a surrogate species because its body morphology and habitat preferences are similar to Asian carp and was locally abundant in the CSSC so as to minimize potential collection handling stress. Clupeidae species such as gizzard shad are generally known to be sensitive to handling stress (e.g. Smith et al. 2009), likely more so than Asian carp. Because of the sensitivity of Gizzard Shad compared to other potential surrogates to Asian carp, we feel that the results obtained are likely conservative.

Gizzard Shad that were used in the caged-fish trials were collected via cast netting during fall 2011 and winter 2011. Later, when fish became more difficult to locate, we collected Giz-
zard Shad via electrofishing for the remainder of the trials. All fish were collected on the same day that the trials took place. Although collection of the Gizzard Shad used in the trials was random in nature, large fish (> 300 mm TL) were not targeted. After the fish were collected, the smallest fish available were used given that small fish are thought to pose the greatest threat to breaching the barrier (Holliman 2011; Parker et al. 2013). All fish were measured after the trials concluded as part of efforts to reduce handling stress.

The cage used in the trials had a non-conductive PVC frame (160-cm L x 58-cm W x 89-cm D) with 0.95-cm bar monofilament mesh. The cage was secured alongside a boat using custom mounts (figure 4). During the first evaluation in the summer of 2011, a DIDSON unit, mounted on the opposite side of the boat, was used to record fish behavior in the cage. However, after the first evaluation with the DIDSON unit, we found that water clarity and visibility allowed us to record fish behavior with a camcorder mounted above the cage. Using a camcorder allowed for faster set up time in the field and allowed for easier navigation of the boat without the DIDSON in the water. Later comparisons of camcorder and DIDSON recordings revealed no differences in reviewer’s ability to interpret fish behavior.
**Figure 4.** Cage mounted on the side of an aluminum boat.

**Figure 5.** Illustration depicting the cage and DIDSON mounting schemes on the north-oriented research boat in the CSSC and the two parts of the canal that the boat travelled. Note: only a single boat was used for caged-fish trials.
Five gizzard shad were placed in the cage and moved through one of the following three 115-m sections of the CSSC moving from south to north (upstream): (a) through the mid-channel of the CSSC over the entire array of electrical barrier structures, (b) along the western canal wall of the CSSC, over the entire array of electrical barrier structures, or (c) a control area through the mid-channel of the CSSC, in non-electrified water (Fig. 6). The upper end of the control trial run was approximately 100-m downstream of all electrical barrier structures and outside of any electrical influences. For the runs that were performed through the electric barrier, the starting point was in an area of non-electrified water. Ten trial runs were performed within each section of the canal per experimental event.

Fish were given 1 min before the trial began to acclimate to the cage in non-electrified water below the electric barrier. After acclimation, we began recording the fish. When the DIDSON was used, a stop watch was started at the same time as the DIDSON. Times were then recorded when the caged fish passed by nine different observation points (Fig. 6; Table 2). These times were later used by workers to record fish behavior at the designated sites. When the camcorder was used, the observation point numbers were announced into the camcorder microphone. These verbal cues were later used in the lab to record fish behavior at the designated points.

Trial evaluations using gizzard shad occurred once during the summer of 2011 when the barrier operating parameters were 0.79 V/cm. All other evaluations occurred at the current operating parameters of 0.91 V/cm. Caged-fish evaluations occurred once during the summer and fall of 2011, and winter 2012 using solely an aluminum-hull boat. In the spring and summer of 2012, caged fish were moved through the electrical barriers using both an aluminum-hull and a fiberglass-hull boat. The trials using both aluminum and fiberglass-hull boats were performed within a two-week period during the spring and summer to reduce temporal variability. Boat speeds
were adjusted continuously throughout the trial runs depending on the swimming speed of the fish used (typically 1.6-3.2 km/h). Fish that became incapacitated after moving through the barrier were observed beyond the barriers to assess recovery rate.
Figure 6. Schematic of the electric barrier within the CSSC where caged-fish were moved through from downstream to upstream. Observation points used in the control runs were the same distances apart but outside of the barrier area. Observation points are where behaviors were later recorded. Note: drawing is not to scale and represents caged-fish observation points if only Barrier IIB was operating. Sites were adjusted accordingly if Barrier IIA was operating.
Table 2. Description of caged-fish observation points.

Recordings of caged fish were reviewed in the laboratory, separately, by two different workers. At each observation point, one of four different behaviors was recorded for each fish: “swimming,” defined as normal movement of the fish keeping pace with the moving boat, “flight,” defined as a deviation from normal swimming behavior including sudden bursts of rapid swimming, multiple, rapid changes in position, and non-directional swimming, “floundering,” defined as a fish struggling to not become impinged on the downstream end of the cage, floundering behavior includes thrashing around against the downstream end of the cage or pushing itself off of the cage momentarily before being swept back down against the cage, and “incapacitation,” which was used when all movement ceased and the fish became impinged against the downstream end of the cage. If the two reviewers assigned conflicting behaviors for a fish at an observation point a third reviewer assigned a behavior. If the third assigned behavior matched one of the previous two assigned behaviors, that behavior was used. If three different behaviors were assigned, for a fish at a particular observation point, no behavioral datum was recorded.

<table>
<thead>
<tr>
<th>Observation point</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Area immediately below the first operating parasitic structure where voltage is minimal</td>
</tr>
<tr>
<td>2</td>
<td>Middle of first operating parasitic structure</td>
</tr>
<tr>
<td>3</td>
<td>Mid-point between parasitic structure and first wide array structure</td>
</tr>
<tr>
<td>4</td>
<td>Middle of downstream wide-array structure</td>
</tr>
<tr>
<td>5</td>
<td>Mid-point between two wide-array structures</td>
</tr>
<tr>
<td>6</td>
<td>Middle of upstream wide-array structure</td>
</tr>
<tr>
<td>7</td>
<td>Middle of downstream narrow-array structure</td>
</tr>
<tr>
<td>8</td>
<td>Mid-point between two narrow-array structures where voltage is highest</td>
</tr>
<tr>
<td>9</td>
<td>Middle of upstream narrow array structure</td>
</tr>
</tbody>
</table>
Demonstration barrier caged-fish trials

On June 12, 2012, nine caged-fish trials were performed within the Demonstration Barrier using 11 Common Carp (391-673 mm TL) and 2 Freshwater Drum (*Aplodinotus grunniens*; 371-384 mm TL). Four observation points were designated for verbal cues to be announced while the camcorder recorded behavior. The first observation point was located 39 m south of the Demonstration Barrier, in non-electrified water. Observation points 2-4 were located at the downstream, middle, and upstream locations of the Demonstration Barrier, which covers 18 m of canal length. All trials were performed using a fiberglass boat.
Statistical Analyses

DIDSON sampling data analyses

Prior to analysis of count data from the DIDSON recordings, the data needed to be standardized to account for unequal volumes of water being ensonified by the DIDSON cone. The DIDSON ensonified the same volume of water at all of the site sub-sections with the exceptions of “A” and “J.” The viewing cone at those sections intersected with the water surface. In geometric terms, the volume of the truncated DIDSON ensonification cone that was lost is referred to as a vertical slice. The vertical slice loss was calculated using mathematical integration by section of the circular cross section of the truncated cone from the cone bottom to the intersection of the water surface. Assuming a distance of eight meters from the DIDSON unit to the canal wall, a loss of 11% of the DIDSON viewing cone was determined. Therefore, the numbers of fish in sections A and J received a weighting of 1.11 in all regression models in order to account for the vertical slice loss; all other sections received a weighting of 1.

The probabilities of individual fish and schooled fish presence were compared across locations (i.e., sites or sections). Specifically, we used binary logistic regression models to determine whether the probability of individual fish presence was different based on the location within the electric barrier (i.e., site or section); the logit-link function was used to transform location-specific probabilities to the natural log of the odds ratio of presence versus absence. Post-hoc odds ratios were used to examine which locations were responsible for significant effects. Odds ratios that were significantly different from one indicate that the probability of individual or school presence is greater in the locations or seasons being compared (Agresti 2007). To more closely examine the spatial differences in section presence of individual or schooled fish within each site, we included both the main effects of site, section, and their interaction; this resulted in
several site and section combinations that had probabilistic estimates of zero or one, thereby inhibiting the number of comparisons on the basis of quasi-complete separation of data points. In other words, too few observations were available to make statistical inferences outside of visual interpretations of estimated probabilities for this model. In all models, beam volume was used as a weighting factor as described above. The effect that fish size has on determining which site a fish was present in was evaluated using a logit model. Wald $\chi^2$ statistics were used to determine whether size had an overall effect on fish distributions throughout the electric barrier. Similar to Becker et al. (2011), one behavioral category was often dominant at each site, leaving insufficient data to perform simple statistical analyses, therefore behavioral data are described.

Durbin-Watson tests were performed on the environmental variables that were recorded during each DIDSON run, which found that those data were highly autocorrelated. Therefore means of those data were taken for the entire sampling period and separate simple linear regressions were performed with mean $\log_e(n+1)$-transformed individual fish abundances and number of fish schools against velocity, dissolved oxygen, temperature, and conductivity. For the regression analyses, alpha was Bonferroni-corrected for multiple comparisons (5 for both individual and number of fish schools), therefore, alpha was set at 0.01.

Stepwise logistic regression was used to evaluate factors influencing fish presence within the zone of ultimate field strength. Independent variables tested in the model were water velocity (m/s), dissolved oxygen (mg/l), pH, conductivity (µs/cm), and temperature (˚C). The environmental data were recorded each time a DIDSON recording took place (every ten minutes). Durbin-Watson tests revealed that the environmental data were autocorrelated within each day that the recordings were taken. Therefore, the mean values of the environmental data were taken for
each day. Separate stepwise logistic regressions were performed modeling the presence (scored a one) absence (scored a zero) of schooled and individual fish during each day.

**Caged-fish data analysis**

Binary logistic regression was used to model the probability of fish incapacitation as a function of distance into the electric barrier from our predetermined starting point (Agresti 2007). Fish that immediately became impinged on the back of the cage when the boat first started moving through non-electrified water, presumably because of previous capture and handling stress, were omitted from analyses, which was 19% of the fish used. By modeling the binary response of each fish randomly assigned to a treatment (control, mid-channel, west wall), each fish was considered to represent a single Bernoulli trial, or replicate, in which only two outcomes were possible (Breen and Ruetz 2006; Agresti 2007; Gotelli and Ellison 2004). However, if the assumption that each fish represents a Bernoulli trial is not approximately true slope and intercept estimates would not be affected, yet the probability of a type I error would be inflated (Breen and Ruetz 2006; Agresti 2007). Initially, the logistic regressions that were performed on the spring, fiberglass-hull boat results had quasi-complete separation of data points (i.e., a specific distance at which all fish went from not being incapacitated to being incapacitated). For convergence and comparative purposes a score of one was artificially added to each observation distance (Allison 2008).

The distance at which 50% of gizzard shad were incapacitated (median incapacitation distance, hereafter) was estimated from the slope and intercept estimates from each logistic regression function. To evaluate the effect of temperature, conductivity, and fish size on median incapacitation distance, a principal components analysis (PCA) was used to reduce the dimensionality of the correlated independent variables into a single value, or PCA score, for each trial
period. This analysis was only performed for the present barrier voltage in which an entire year of data was available. Median incapacitation distances were log-transformed to homogenize variances and a linear regression was used to examine the relationship between PC 1 scores and median incapacitation distance. A Pearson correlation between the PC scores 1 and 2 and the independent variables was performed in order to assess relationships between the individual variables and the PC scores. A lack of within-season replication precluded analyses relative to the effects of canal location (canal wall or mid-channel) and boat hull material, so results are described.
Results

Former Operating Parameters (0.79 V/cm) Fish behavior and abundance near the barriers

During the summer of 2011, 750 individual fish and 570 different schools of fish were observed within and around the electric barrier. The probability of individual fish presence differed among sites (Wald $\chi^2 = 71.11$; df = 7; $P < 0.001$), as did the probability of schooled fish presence (Wald $\chi^2 = 51.57$; df = 7; $P < 0.001$), with the highest probabilities being observed at sites 1-4 for both individual fish (Fig. 7) and schooled fish (Fig. 8), which are below the low-field electrical arrays. However, some fish were observed further into the electric barrier, including site six, which is between the narrow arrays (Fig. 7 and Fig. 8) that contained the ultimate field strength of 0.79 V/cm.

The probability of individual fish presence was not different among sections when pooled across sites (Wald $\chi^2 = 12.20$; df = 9; $P = 0.202$), with a 0.92 probability of presence across all sections (95% CI = 0.90 – 0.93). Schooled fish probability of presence on the other hand did vary among sections pooled across sites (Wald $\chi^2 = 45.11$; df = 9; $P < 0.001$), with higher probabilities of presence closer to the canal walls (Fig. 9). Within each site, both individual fish and schools of fish (Fig. 10) utilized the majority of the sections in sites one through four. However, within the sites that were in the highest-voltage water and upstream of the barriers, the fish had a higher probability of being present near the canal walls, particularly the east wall.
Figure 7. Probability of individual fish presence at sites 1-8 within the electric dispersal barrier in summer 2011 (pooled across sections). Bars with the same letters indicate statistically similar odds ratio estimates between sites ($P > 0.05$).
Figure 8. Probability of schooled fish presence at sites 1-8 within the electric dispersal barrier in summer 2011 (pooled across sections). Bars with the same letters indicate statistically similar odds ratio estimates between sites ($P > 0.05$).
Figure 9. Probability of schooled fish presence at sections A-J within the electric dispersal barrier in summer 2011 (pooled across sites). Bars with the same letters indicate statistically similar odds ratio estimates between sections ($P > 0.05$).
Figure 10. Probabilistic estimates of individual fish and schooled fish presence plotted across sites and sections within the electric dispersal barrier from summer 2011.

We found that for both individual (Fig. 11; Wald $\chi^2 = 134.63$, $P < 0.0001$) and schooled fish (Fig. 12; Wald $\chi^2 = 83.37$, $P < 0.0001$), size was a significant factor in determining which site fish were present in. Larger fish had the greatest probability of being present at sites one through four. At sites five through eight, small fish had the highest probabilities of being present.
Figure 11. Probability models for individual fish presence based on size at each site. Black lines represent predicted probabilities and gray lines represent 95% confidence intervals.
Figure 12. Probability models for schooled fish presence based on size at each site. Black lines represent predicted probabilities and gray lines represent 95% confidence intervals.
For both individual fish and schools of fish, swimming was the dominant behavior that was observed at all sites with the electric barrier. Hovering behavior increased when fish were closer to the barriers, and peaked at sites 5 and 6, most likely because those fish were between barrier arrays. Site 4 was the only site where fish displayed all four possible behaviors (fig. 13; 14). Fish that encountered the barrier were often observed swimming both up and down and sideways along the electrical field, fish were also observed swimming into the electrical field and then returning downstream. None of the linear regressions relating numbers of individual fish and schools of fish to environmental variables were significant at alpha = 0.01 given the low power of detection (p ≥ 0.017)
Figure 13. Percentages of different behaviors observed by individual fish at the different sites within the electric barrier in the CSSC.
Figure 14. Percentages of different behaviors observed by schools of fish at the different sites within the electric barrier in the CSSC.
Former Operating Parameters (0.79 V/cm) Caged-fish trials

Of the 270 fish that were pulled through the electric barrier, 3% did not become incapacitated (n=4 through the mid-channel and n=4 along the west canal wall). One of the fish that was moved through the mid-channel exhibited erratic swimming, in which it was briefly impinged on the back of the cage (but still moving); the other seven fish swam the entire time while moving through the barriers. The estimated slopes and intercepts for the logistic regression models for all run locations were significant (p < 0.001) at the lower operating parameters. The logistic regression model for the control runs showed a low probability of fish becoming incapacitated as a result of being forced to swim along a boat while caged and the proportion of variability explained was very low (generalized $R^2 = 0.38$, slope = -3.69 [SE ± 0.357], intercept = 0.01 [SE ± 0.004]; Fig. 15). The logistic regression models for the mid-channel (generalized $R^2 = 0.74$, slope = -4.09 [SE ± 0.265], intercept = 0.06 [SE ± 0.003]) and west wall (generalized $R^2 = 0.75$, slope = -5.008 [SE ±0.328], intercept = 0.07[SE ± 0.004]) runs had higher proportions of variability explained relative to the control location given that distance was a better predictor for incapacitation. The median incapacitation distances were 66 m in the mid-channel and 73 m along the west wall (Fig. 15). The average sizes of fish (mm ± SE) used in the control, mid-channel, and canal wall trials were 126.7 (5.72), 123.7 (5.73), and 111.3 (3.03) respectively. The average water conductivity was 0.74 mS/cm (SE ± 0.003), and average water temperature was 24.2 °C (SE ± 0.105).

Swimming and incapacitation were the most common behaviors recorded. Swimming was the most common recorded behavior for the control runs (fig. 16). Swimming behavior decreased steadily as fish were moved further into the electric barrier in both the mid-channel and
along the west wall. Flight and floundering behavior, while low, occurred mostly at sites one through five before fish became incapacitated (figs. 17;18).
Figure 15. Predicted incapacitation probabilities of encaged gizzard shad as a function of distance at different locations with the barrier operating at 0.79 V/cm. Lines extending from x and y axes denote predicted point at which half of the fish became incapacitated (mid-channel and west wall only). Points represent the means (± SE) of observations at site distances, but the model is based on actual observations (0 or 1). Shaded areas represent locations of wide and narrow barrier arrays.
Figure 16. Percentages of different recorded behaviors for caged fish at each observation point in the control area.
Figure 17. Percentages of different recorded behaviors for caged fish at each observation point in the mid-channel of the electric barrier.
Figure 18. Percentages of different recorded behaviors for caged fish at each observation point along the west wall of the electric barrier.

Current Operating Parameters (0.91 V/cm)  Fish behavior and abundance near the barriers

Throughout the winter, spring, summer, and fall of 2012 we respectively sampled 74, 41, 45, and 123 individual fish and 46, 46, 215, and 246 schools of fish. The probability of individual fish presence differed among sites (Wald $\chi^2 = 18.75$; df = 7; $P = 0.009$) and seasons (Wald $\chi^2 = 25.96$; df = 3; $P < 0.001$), yet site-specific probabilities of individual fish presence were not consistent across seasons (Wald $\chi^2 = 39.77$, df = 21, $P = 0.008$). In general, the odds of individual fish presence across all sites was greater in the fall compared to the summer (Wald $\chi^2 = 25.96$;
Within-season differences of the probability of individual fish presence among sites occurred in the winter (Wald $\chi^2 = 22.47$, df = 7, $P = 0.002$), summer (Wald $\chi^2 = 22.12$, df = 7, $P = 0.002$), and spring (Wald $\chi^2 = 18.21$, df = 7, $P = 0.011$), but were not different in the fall (Wald $\chi^2 = 11.77$, df = 7, $P = 0.108$; Figure 19). Probabilities of observing schooled fish at specific sites also differed seasonally (Wald $\chi^2 = 60.59$, df = 21, $P < 0.001$); the main effects of site (Wald $\chi^2 = 0.0004$; df = 7; $P = 1.00$) and season (Wald $\chi^2 = 0.0004$; df = 7; $P = 1.00$) were not significant. Probabilistic estimates of fish school presence were different among sites in the summer (Wald $\chi^2 = 37.94$, df = 7, $P < 0.001$) and fall (Wald $\chi^2 = 31.42$, df = 7, $P < 0.001$), but were not different in the winter (Wald $\chi^2 = 4.47$, df = 7, $P = 0.724$) or spring (Wald $\chi^2 = 8.90$, df = 7, $P = 0.260$; Fig. 20). Both the individual and schooled fish were largely absent from sites 4-6 during the winter and spring periods. However, fish began to penetrate further into the barriers in the summer and by the fall, with both individual and schooled fish observed as far into the barrier as site six (Figs. 23 and 24) which contains the ultimate field strength of 0.91 V/cm.
Figure 19. Season-specific probabilities of individual fish presence at sites 1-8 within the electric dispersal barrier throughout 2012 (pooled across sections). Bars with similar letters indicate statistically similar odds ratio estimates between sites within a season ($P > 0.05$). An asterisks (*) indicates that individual fish were never observed at these sites such that no valid comparisons were possible.
Figure 20. Season-specific probabilities of schooled fish presence at sites 1-8 within the electric dispersal barrier throughout 2012 (pooled across sections). Bars with similar letters indicate statistically similar odds ratio estimates between sites within a season (P > 0.05). An asterisks (*) indicates that schooled fish were never observed at these sites such that no valid comparisons were possible.

We found that when comparing fish presence among all sites, that schooled fish exhibited differential use of sections across seasons (Wald $\chi^2 = 45.82$, df = 27, P = 0.013). Within-season probabilities of schooled fish presence differed among sections in the winter (Wald $\chi^2 = 19.70$; df = 9; P = 0.020) and fall (Wald $\chi^2 = 28.47$; df = 9; P < 0.001), but was not different in the spring (Wald $\chi^2 = 12.18$; df = 9; P = 0.204) or summer (Wald $\chi^2 = 11.00$; df = 9; P = 0.276; Figure 21). Individual fish also exhibited differential use of sections across seasons (Wald $\chi^2 = 55.65$, df = 27, P = 0.001). Within-season probabilities of individual fish presence differed among sections.
in the winter (Wald $\chi^2 = 41.10; df = 9; P < 0.001$) and fall (Wald $\chi^2 = 20.65; df = 9; P = 0.014$), but was not different in the spring (Wald $\chi^2 = 10.46; df = 9; P = 0.314$) or summer (Wald $\chi^2 = 10.03; df = 9; P = 0.3484$; Fig. 22). Within sites 1-3 and site 8, both individual fish (Fig. 23) and schools of fish (Fig. 24) utilized the majority of the sections. However, within the other sites that were closer to the electrified portions of the barrier, the fish had a higher probability of being present near the canal walls.

**Figure 21.** Season-specific probabilities of schooled fish presence at sections A-J within the electric dispersal barrier throughout 2012 (pooled across sites). Bars with similar letters indicate statistically similar odds ratio estimates between sections within a season ($P > 0.05$). An asterisks (*) indicates that schooled fish were never observed at these sections such that no valid comparisons were possible.
Figure 22. Season-specific probabilities of individual fish presence at sections A-J within the electric dispersal barrier throughout 2012 (pooled across sites). Bars with similar letters indicate statistically similar odds ratio estimates between sections within a season ($P > 0.05$). An asterisks (*) indicates that individual fish were never observed at these sections such that no valid comparisons were possible.
Figure 23. Probabilistic estimates of individual fish presence plotted across sites and sections within the electric dispersal barrier for each season within 2012. The lack of replicated observation events in spring, summer, and fall 2012 resulted in site and section probabilistic estimates to be either 0 or 1.
Figure 24. Probabilistic estimates of schooled fish presence plotted across sites and sections within the electric dispersal barrier for each season within 2012. The lack of replicated observation events in spring, summer, and fall 2012 resulted in site and section probabilistic estimates to be either 0 or 1.
We found that size was only a significant factor in determining which sites fish were present in for individual fish in the fall season (Fig. 25; Wald $\chi^2 = 18.45$, df = 7, $P = 0.010$) and schooled fish in the summer season (Fig. 26; Wald $\chi^2 = 33.20$, df = 6, $P < 0.0001$) and did not have an effect in other seasons for individuals or schools. Larger fish had the greatest probability of being present at sites 1-3. At sites 4-8, small fish had higher probabilities of being present. For both individual fish and schools of fish, in all seasons, swimming was the dominant behavior that was observed at all sites within the electric barrier. Hovering behavior increased when fish were closer to the barriers (Fig. 27; 28).
Figure 25. Probability models for fall season, individual fish presence based on size at each site. Black lines represent predicted probabilities and gray lines represent 95% confidence intervals.
Figure 26. Probability models for summer season, schooled fish presence based on size at each site. Black lines represent predicted probabilities and gray lines represent 95% confidence intervals. Note: no information is presented for site six because no fish schools were present at that time.
Figure 27. Proportions of different behaviors observed by individual fish at the different sites within the electric barrier in the CSSC.
Figure 28. Proportions of different behaviors observed by schooled fish at the different sites within the electric barrier in the CSSC.
The concentrated DIDSON sampling within the zone of ultimate field strength revealed a low amount of fish activity in that area during the spring with only 16 individuals and 1 school of fish observed. However, in the summer, fish activity in that area increased with 143 individuals and 238 schools of fish observed. Stepwise logistic regression models revealed that dissolved oxygen concentrations and temperature were the most informative variables explaining presence/absence of schooled fish within the zone of ultimate field strength ($\chi^2 = 12.37$, df = 2, $P = 0.0021$; Table 3). Dissolved oxygen concentration alone was most informative when explaining individual fish presence/absence ($\chi^2 = 6.46$, df = 1, $P = 0.0110$; Table 4). The average size of both schooled (Fig. 29A) and individual (30A) fish that were present within the zone of ultimate field strength decreased from the early spring to late summer.

<table>
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<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Wald $\chi^2$</th>
<th>df</th>
<th>$P$</th>
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<tr>
<td>Intercept</td>
<td>-24.24</td>
<td>5.64</td>
<td>1</td>
<td>0.018</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>7.96</td>
<td>6.46</td>
<td>1</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Table 3. Summary of stepwise logistic regression models used to estimate the probability of individual and schooled fish presence/absence at the zone of ultimate field strength.
Figure 29. Mean sizes of schooled fish present at the zone of ultimate field strength (A) and mean dissolved oxygen concentrations (B) and temperatures (C). Each bar represents a single day of sampling in April, May, July, and September 2012. Hatch marks in dissolved oxygen and temperature bars indicate days in which a school of fish was present in the zone of ultimate field strength.

Figure 30. Mean sizes of individual fish present at the zone of ultimate field strength (A) and mean dissolved oxygen concentrations. Each bar represents a single day of sampling in April, May, July, and September 2012. Hatch marks in dissolved oxygen bars indicate days in which individual of fish were present in the zone of ultimate field strength.
Flight, hovering, and probing behaviors were observed much more during the concentrated DID-SON sampling within the zone of ultimate field strength, although swimming was still the most dominant behavior (Fig. 31). Fish that encountered the barrier were often observed swimming both up and down and sideways along the electrical field, fish were also observed swimming into the electrical field and then returning downstream. The fish that were observed penetrating the furthest upstream into the zone of ultimate field strength attempted to move further upstream by swimming mostly perpendicular to the canal flow, but also moving slightly upstream. As they swam, the fish changed the direction of perpendicular movement rapidly. This behavior was interpreted to be body-voltage minimizing behavior.

Figure 31. Proportions of different behaviors observed by individual and schooled fish during the spring and summer of 2012 at the zone of ultimate field strength in the barrier.
Current Operating Parameters (0.91 V/cm) Caged-fish trials

All fish that were moved through the barriers, at the current operating parameters of 0.91 V/cm, were incapacitated at some point. The probability of incapacitation was strongly related with distance into the electric barrier as indicated by significant slope values for all but two trials, one of which was a control (Table 4). The distance into the electric barrier in which fish became incapacitated varied widely, however, depending on season, which part of the canal fish were moved through (mid-channel or along west wall), or the type of boat used (fiberglass or aluminum hull) (Fig. 32). Fish that were moved through the barriers in the winter and spring became incapacitated the soonest, whereas during the summer, when fish were moved along an aluminum vessel, the fish swam the furthest into the electric barrier. During all seasons, fish that were moved through the barrier along the canal wall advanced farther into the barrier before becoming incapacitated than those that were moved through the middle of the canal (Table 4). All fish that were moved through the electric barrier recovered in less than one minute post-incapacitation.

The PCA analysis revealed a temperature-conductivity gradient along the first principal component, and revealed distinct groupings among fish sizes and the two environmental variables between seasons (Figure 33; Table 5). The second axis (PC2) showed a weak size gradient (Figure 33; Table 5). The first and second principal component axes explained 72% and 24% of the variation in the correlation matrix respectively. The fish used in the trial runs were largest in the spring and winter when temperatures were lowest and conductivity was highest. The linear regression between PC 1 scores and incapacitation distances revealed a significant inverse relationship ($R^2 = -0.60$, $p = 0.003$; Fig. 34).
Table 4. Mean total length of gizzard shad used in trials, predicted distances at which 50% of the caged fish would be incapacitated, generalized coefficients of determination ($R^2$) and estimated logistic regression slopes and intercepts under various conditions. Results are only for trial runs that took place at the current barrier operating parameters.

<table>
<thead>
<tr>
<th>Season</th>
<th>Conductivity (mS/cm ± SE)</th>
<th>Temperature (°C ± SE)</th>
<th>Barrier Location</th>
<th>Boat Vessel</th>
<th>Mean Fish Size (mm ± SE)</th>
<th>50% Incapacitation Distance (m)</th>
<th>Generalized $R^2$ (± SE)</th>
<th>Estimated Slope (± SE)</th>
<th>Estimated Intercept (± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>0.89 (0.009)</td>
<td>12.53 (0.139)</td>
<td>Control</td>
<td>Aluminum</td>
<td>129.5 (1.72)</td>
<td>-</td>
<td>0.33</td>
<td>-3.86 (0.531)*</td>
<td>0.01 (0.006)*</td>
</tr>
<tr>
<td>Fall</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>123.6 (2.04)</td>
<td>61</td>
<td>0.73</td>
<td>-5.80 (0.558)</td>
<td>0.10 (0.008)*</td>
</tr>
<tr>
<td>Winter</td>
<td>1.16 (0.003)</td>
<td>9.30 (0.082)</td>
<td>Control</td>
<td>Aluminum</td>
<td>132.8 (2.79)</td>
<td>-</td>
<td>0.54</td>
<td>-3.97 (0.633)*</td>
<td>0.03 (0.007)*</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>132.2 (6.29)</td>
<td>31</td>
<td>0.65</td>
<td>-3.69 (0.837)*</td>
<td>0.12 (0.026)*</td>
</tr>
<tr>
<td>Spring</td>
<td>0.97 (0.010)</td>
<td>15.41 (0.029)</td>
<td>Control</td>
<td>Aluminum</td>
<td>211.6 (1.37)</td>
<td>-</td>
<td>0.38</td>
<td>-4.29 (0.539)*</td>
<td>0.02 (0.006)*</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>212.8 (1.28)</td>
<td>31</td>
<td>0.66</td>
<td>-8.18 (1.559)*</td>
<td>0.27 (0.047)*</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>216.8 (1.38)</td>
<td>32</td>
<td>0.66</td>
<td>-5.39 (0.815)*</td>
<td>0.17 (0.024)*</td>
</tr>
<tr>
<td>Spring</td>
<td>1.10 (0.005)</td>
<td>15.40 (0.019)</td>
<td>Control</td>
<td>Fiberglass</td>
<td>213.0 (2.67)</td>
<td>-</td>
<td>0.64</td>
<td>-2.27 (0.359)*</td>
<td>0.01 (0.004)*</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Fiberglass</td>
<td>224.3 (1.17)</td>
<td>32</td>
<td>0.66</td>
<td>-2.68 (0.383)*</td>
<td>0.09 (0.010)*</td>
</tr>
<tr>
<td>Summer</td>
<td>0.76 (0.004)</td>
<td>26.10 (0.210)</td>
<td>Control</td>
<td>Aluminum</td>
<td>115.2 (2.15)</td>
<td>-</td>
<td>0.35</td>
<td>-3.80 (0.639)</td>
<td>0.01 (0.007)*</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>122.7 (2.38)</td>
<td>76</td>
<td>0.75</td>
<td>-5.41 (0.646)*</td>
<td>0.07 (0.007)*</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Aluminum</td>
<td>118.2 (2.83)</td>
<td>81</td>
<td>0.75</td>
<td>-3.86 (0.468)</td>
<td>0.05 (0.005)*</td>
</tr>
<tr>
<td>Summer</td>
<td>0.67 (0.026)</td>
<td>25.04 (0.081)</td>
<td>Control</td>
<td>Fiberglass</td>
<td>105.8 (1.80)</td>
<td>-</td>
<td>0.60</td>
<td>-2.85 (0.408)*</td>
<td>0.02 (0.004)*</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Fiberglass</td>
<td>117.8 (3.39)</td>
<td>41</td>
<td>0.69</td>
<td>-3.21 (0.437)*</td>
<td>0.08 (0.009)*</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td>Canal Wall</td>
<td>Fiberglass</td>
<td>116.0 (2.78)</td>
<td>51</td>
<td>0.72</td>
<td>-3.36 (0.403)*</td>
<td>0.07 (0.006)*</td>
</tr>
</tbody>
</table>

*P < 0.05
Figure 32. Predicted relationships of the incapacitation probabilities of encaged Gizzard Shad as a function of distance during different seasons and alongside different boat hulls (spring and summer only [during the fall and winter, only aluminum-hull boats were used]). Lines extending from x and y axes denote predicted point at which half of the fish became incapacitated. Points represent the means (± SE) of observations at site distances, but model is based on actual observations (0 or 1).
Figure 33. Principal components analysis bi-plot of three continuous variables measured during trial runs. Arrows represent eigenvectors multiplied by two to scale to bi-plot area.
Figure 34. Regressions of principal component 1 and barrier-run, incapacitation distances (natural-log transformed). Diamonds (♦) denote trial runs along the canal wall with an aluminum-hull boat, squares (■) denote trial runs along the canal wall with a fiberglass-hull boat, triangles (▲) denote trial runs through the mid-channel of the canal with an aluminum-hull boat, and circles (●) denote trial runs through the mid-channel of the canal with a fiberglass boat.

Table 5. Correlation matrix of PC 1 and 2 scores with environmental and size variables.

<table>
<thead>
<tr>
<th></th>
<th>Conductivity (mS/cm)</th>
<th>Temperature (°C)</th>
<th>Fish Size (mm TL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal component 1</td>
<td>0.96*</td>
<td>-0.89*</td>
<td>0.68*</td>
</tr>
<tr>
<td>Principal component 2</td>
<td>-0.13</td>
<td>0.42</td>
<td>0.73*</td>
</tr>
<tr>
<td>Conductivity</td>
<td>-0.86*</td>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td>-0.31</td>
</tr>
</tbody>
</table>

* Indicates significance at the p < 0.05 level.
Six out of the eleven encaged Common Carp that were moved through the Demonstration Barrier were not incapacitated. However, all of those Common Carp that were not incapacitated did display reactions such as rapid circling motions within the cage and, in some cases, attempting to swim downstream as they were being moved through the barrier upstream. The two Freshwater Drum that were moved through the barrier were not incapacitated nor did they display any type of behavior indicating that they were in distress (Table 6). A logistic regression modeling the probability of incapacitation as a function of distance into the barrier was not significant (slope $P = 0.16$). This is likely due to the small sample size entered into the model.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Run location</th>
<th>Species</th>
<th>Length (mm TL)</th>
<th>Incapacitated?</th>
<th>Avoidance Behavior?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mid-channel barrier</td>
<td>Common Carp</td>
<td>396</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>2</td>
<td>west wall</td>
<td>Common Carp</td>
<td>490</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>3</td>
<td>Mid-channel barrier</td>
<td>Freshwater Drum</td>
<td>371</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>4</td>
<td>west wall</td>
<td>Common Carp</td>
<td>465</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Mid-channel barrier</td>
<td>Freshwater Drum</td>
<td>384</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>6</td>
<td>west wall</td>
<td>Common Carp</td>
<td>526</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>7</td>
<td>Mid-channel barrier</td>
<td>Common Carp</td>
<td>483</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>west wall</td>
<td>Common Carp</td>
<td>653</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>9</td>
<td>Mid-channel barrier</td>
<td>Common Carp</td>
<td>589</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>9</td>
<td>Mid-channel barrier</td>
<td>Common Carp</td>
<td>673</td>
<td>YES</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.** Trial run information for large fish used in Demonstration Barrier caged-fish evaluations.
Discussion

During the winter and spring, very few fish were present near the barriers and the ones that were, were not present in the strongest parts of the barrier. During the summer, at both the former and current operating parameters, more fish began to occupy the barrier area, yet there was an abrupt decrease in the number of fish observed in the strongest parts of the barrier. However, both our standard and concentrated DIDSON sampling revealed that during the fall, the fish were most abundant immediately below the barriers and more likely to actively challenge the barriers. The large accumulations and challenging of the barriers occurred both at the reduced and current operating parameters in the late summer/early fall. In fact, we observed no differences amongst individual fish distribution around the wide and narrow arrays in the fall (current operating parameters). The distributions of fish schools during the fall, at the current operating parameters, were not homogenous, but the differences between the sites within the zone of ultimate field strength and the sites with low/no voltage was less distinct as in the other seasons. This difference between the individual and schooled fish may be because the schooled fish tended to mostly occupy the canal walls, at the water surface, as shown with both the standard and concentrated DIDSON sampling. Because the schools were concentrated in such small areas, once they entered the zone of ultimate field strength, which were only sampled for ten minutes during our standard DIDSON sampling, individual fish were observed to be more prevalent in the zone of ultimate field strength than the schools. However, many more schools of fish within the zone of ultimate field strength were observed than individuals. Holliman (2011) found that schools of small Bighead Carp were more likely to challenge a laboratory barrier than individual fish. Also, in a separate study, we observed numerous breaches of the CSSC barrier by schools.
of fish, whereas individual, and even loosely aggregated fish were unable to breach the barrier (Parker et al. 2013).

We found that although fish accumulated below the barrier in the summer, they were homogenously distributed amongst site sections, indicating that they were most likely swimming back and forth, probing the barrier, but not actively challenging it as much. However, in the fall, fish were observed more near the canal walls, at the water surface. This is most likely because the fish were more actively challenging the barrier, and that near the canal walls, at the surface, is where the barrier voltage is weakest (Holliman et al. 2011). Also, the results of our caged-fish work (discussed below) revealed that the fish always took slightly longer to become incapacitated when moved along the canal wall, compared to the mid-channel. Based on these results, the barrier seems least susceptible to breach during the winter and spring. In the summer and fall though, the barrier is particularly susceptible to breach because of the amount of fish present and the increased activity levels. Increased activity and movement of temperate zone fishes in warmer weather is typical (e.g. Gauthreaux 1980). Because of this, it is recommended that any necessary barrier maintenance shut-downs should be performed in the winter as much as possible, and avoided during the summer and fall.

During our concentrated efforts, numerous instances of large schools of fish repeatedly challenging the barrier were observed. We found that a combination of high water temperatures coupled with dissolved oxygen concentrations at or greater than around 4 mg/l appears to explain the high amount of barrier challenging behavior by resident fish of the CSSC. On several occasions, fish were observed to be swimming through the entire DIDSON viewing cone that was ensonifying the water surface within the zone of ultimate field strength. However, because a single DIDSON viewing cone could not ensonify the entire width of the ultimate field strength
zone, no definitive conclusions could be made as to whether fish had actually breached the barrier by swimming all the way through it. However, recently, in the summer of 2013, two fixed-position DIDSON units simultaneously recorded the entire width of the ultimate field strength zone. With the two units, we recorded numerous instances of schools of small (<2 in), wild fish breaching the barrier (Parker et al. 2013).

Fish size was a significant factor affecting the degree to which wild fish could penetrate into the barriers during the summer and fall with the smaller fish being able to penetrate the furthest. During the winter and spring, we saw mostly larger fish, with the smallest ones being age-1 fish from the previous year. In fact, as discussed in the materials and methods, the smallest Gizzard Shad that we could locate in the spring were greater than 200 mm TL. However, during the summer and fall is when that year’s young-of-the-year began occupying the canal and began penetrating the barrier further than any other fish had. Holliman (2011) also found that smaller Bighead Carp were able to penetrate further into an electrical barrier in a laboratory setting before movement was either inhibited or a breach occurred. The phenomenon of water-borne electricity affecting larger fish more than smaller fish has been well-established based on electrofishing studies (Reynolds 1996; Ruetz et al. 2007).

The movement of caged fish alongside a boat for research purposes is still a rather novel approach. The low number of fish that became incapacitated during our control trials validates our methodology of moving fish through the barriers in cages without the cages having a significant effect. Although all of the caged fish that we moved through the barriers were eventually incapacitated, the distance into the barrier at which they were immobilized varied widely depending on season and the relative conductivity of the hull type used.
After barrier operating parameters were increased, all fish were incapacitated in this study. Variation in the distance at which the fish became incapacitated at the increased parameters was dependent on a combination of water temperature, fish size, canal location (near wall or mid-channel), and boat material the fish were next to during transport. Incapacitation occurred at shorter distances into the electric barrier with larger fish and cooler temperatures (i.e., spring and winter) relative to the smaller fish and warmer temperatures observed during the summer.

Conductivity in the CSSC is inversely related to temperature as a result of heavy winter road salt application in the city of Chicago (Holliman 2011). Typically high conductivities decrease the effect of electricity on fish (e.g. Reynolds 1996). However, the cooler temperatures likely compensate for the potential reduction in effectiveness, as evidenced by the shortest incapacitation distances occurring during the highest conductivity observations.

We observed that the fish used in the winter were lethargic and swam very slowly during the trials prior to incapacitation. We suggest that these results offer a line of evidence that the barrier is least susceptible to breach during the winter. Reduced movement and activity of temperate zone fishes during colder months has been well documented (e.g. Gauthreaux 1980). The short distances into the barrier that the spring fish became incapacitated were likely influenced by their larger size than cooler water temperature. Temperatures were higher in the spring relative to the fall, yet fish were incapacitated sooner in spring than fall. We used the smallest fish that were available to us for the spring trials. However, the fish that we used were likely age-1 fish from the previous year. Our results indicate that larger fish size (>200 mm TL) is as effective at reducing fish penetration into the barrier as cold temperatures. Numerous studies relative to the effects of electrofishing have revealed a positive relationship between fish size and electrical effectiveness (e.g. Reynolds 1996).
The caged fish results during the summer showed the largest discrepancy relative to the effect of the type of boat hull used for trials. Although the gizzard shad were of similar size, the fish that were moved along the aluminum-hull boat were able to swim nearly twice the distance into the barrier as those that were moved along the fiberglass-hull boat. Others have found that steel-hulled barges and aluminum boats conduct electricity as they traverse the barrier in the CSSC (Dettmers et al. 2005; McInerney et al. 2011; Slater et al. 2011), which can create voids of non-electrified water that fish can swim unaffected in (Parker and Finney 2013). We also found that, in all seasons, fish were able to swim into the barrier slightly farther along the canal wall, indicating that the wall may be conducting electricity, and therefore weakening barrier effectiveness as a fish deterrent or for immobilization.

The results of our caged-fish work at the Demonstration Barrier showed that caged fish could pass without incapacitation. Dettmers et al. (2005) found that all caged fish > 150 mm TL were incapacitated by the Demonstration Barrier along both the barge and a fiberglass boat. However, when Dettmers et al. (2005) conducted their caged-fish trials in 2003, the Demonstration Barrier was operating at 0.39 V/cm. Today, as a result of age and deterioration, the Demonstration Barrier operates at about 0.31 V/cm (McInerney et al 2011). While six Common Carp were moved through the barrier without becoming incapacitated, it is important to note that all of those fish did exhibit “avoidance behavior,” such as rapid circling and attempting to swim downstream. The two Freshwater Drum, however, were not incapacitated, nor did they exhibit any sort of “avoidance behavior” to indicate that they were in distress as they were being moved through the Demonstration Barrier. Vulnerability to water-borne electricity can vary among species (Henry et al. 2004) as a result of differences in morphology, physiology, and behavior (Reynolds
Where Asian carp are in the gradient of electrical susceptibility, compared to Freshwater Drum and Common Carp, is currently unknown.

The accumulation of fish below the barrier is not surprising given that fish migrate upstream in lotic systems for numerous reasons such as foraging, migration, reproduction, and escape from predation (Northcote 1978; Dingle 1980; Stewart 1990). Our observations of the fish continuously probing and challenging the barrier is consistent with other findings of fish repeatedly challenging an electrical barrier (Stewart 1981; Savino et al. 2001; Holliman 2011). In some cases, fish that have a strong desire to move upstream will continuously challenge an electrical barrier until they breach it, are harmed, or even killed (Stewart 1990; Bullen and Carlson 2003). Because of this, Stewart (1990) proposed that barriers should be used to modify a particular fish behavior rather than outright prevent it.

Both Bighead and Silver Carp have been shown to exhibit positive rheotaxis and make long upstream dispersals (Peters et al. 2006; DeGrandchamp et al. 2008; Holliman 2011; Hoover et al. 2012). Holliman (2011) found that when small Bighead Carp were placed in a laboratory raceway with flowing water and a small electrical barrier that the fish continuously challenged the barrier. Some fish even re-challenged the barrier immediately upon regaining muscle control after being incapacitated and swept downstream out of the electrical field. This persistent challenging of the electrical field resulted in some fish breaching the barrier at the current operating parameters of 0.91 V/cm (Holliman 2011).

The upstream extent of young-of-the-year Asian carp in the Illinois River, which would pose the greatest threat to barrier breach, have been documented about 164 km below the barriers (http://www.asiancarp.us/documents/ACDistribution.pdf). In December 2009 an adult Bighead Carp was captured just below the barriers in the Lockport Pool during a rotenone event, and in
June 2010 an adult Bighead Carp was captured in Lake Calumet, which is 48 km upstream of the electric barrier (Moy et al. 2011). Also, environmental DNA (eDNA) of both Bighead and Silver Carp has been detected above the barrier system in the CAWS (ACRCC 2013; Jerde et al. 2011; 2013; Mahon et al. 2013).

The discovery of a small number of Asian carp further away from the larger, established population is consistent with numerous other examples of leptokurtic dispersal patterns, in which a few bold individuals move much further than the majority of the population (Skalski and Gilliam 2000; Fraser et al. 2001; Rehage and Sih 2004; Roberts and Angermeir 2007) including invasive fish (Jones and Stuart 2009; Lynch and Mensinger 2012). Furthermore, invasive species often exhibit lag times from the period in which they are initially introduced to a novel habitat, to when they disperse widely (Williamson 1996; Crooks and Soulé 1999; Nico and Fuller 1999) and once established, recruitment may be variable (Madenjian et al. 2005; Weber and Brown 2013). This dispersal lag time phenomenon was displayed by Asian carp as well (Chick and Pegg 2001) and current recruitment in the Illinois River is variable (Irons et al. 2011). Asian carp initially invaded the lower Mississippi River in the 1970’s; however, they did not expand and increase in large numbers in the Illinois River until the 1990’s (Chick and Pegg 2001).

Of great concern is when Barrier IIB (the upstream barrier) is de-energized, either as part of a planned maintenance event or an unplanned outage. In order to properly maintain Barrier IIB, maintenance must be performed at least four times per year. This requires keeping Barrier IIA energized and then de-energizing Barrier IIB. Barrier IIA is downstream of site 2 in figs 2-7 and 2-8, meaning that any fish that are between those two barriers could opportunistically move upstream. Others have found that fish will move upstream soon after an electrical barrier is de-energized (Stewart 1981; Swink 1999; Godlewska et al. 2007; Holliman 2011). In the event that
fish opportunistically move upstream as a result of Barrier IIB being de-energized, movement may still be inhibited by the Demonstration Barrier. However, the Demonstration Barrier is most likely only effective on larger fish because of the age and subsequent deterioration of the structure (McInerney et al. 2011). Current management strategies to address this issue have been to target and capture large fish (≥ 300 mm TL) that are between Barrier IIA and the Demonstration Barrier following an outage or switch. However, these removal efforts have taken place anywhere from one to six weeks following an outage or barrier switch and have never removed all of the large fish that were between the barriers.

Also of concern is the potential for barge vessels to facilitate fish passage beyond the barriers. Besides the metal hull distorting the electric field (Dettmers et al. 2005; McInerney et al. 2011; Slater et al. 2011), barges also create a complex suite of hydrodynamic water motions as they navigate through riverine waterways (Bhowmik and Mazumder 1990; Maynord and Siembre 1990; Wolter and Arlinghaus 2003). The direct (Killgore et al. 2001; Gutreuter et al. 2003; Wolter and Arlinghaus 2004; Killgore et al. 2011) and indirect (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. Currently, laboratory and field studies on the effects of barges on fish near the electric dispersal barrier are being conducted by USACE and USFWS. Preliminary results have revealed multiple modes in which barge vessels can facilitate fish breach (Parker and Finney 2013).

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 (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 is navigating upstream, or a temporary reverse flow if the vessel is navigating downstream (Bhowmik 1991). The magnitude and extent of these water movements is dependent on the size and displacement 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 a confined channel. 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 riverine system with sloped banks that can attenuate wave and flow energy. The section of the CSSC that encompasses the electric barrier is rectangular in cross-sectional shape and is a confined channel.

We observed small fish immediately downstream of the electrical field that encompasses the ultimate field strength of 0.91 V/cm, which is about 2 meters wide at the surface. Larger fish (>300 mm TL) were as close as 35 meters away from that field. Based on the complex barge hydrodynamics described above, both upstream and downstream-bound barges present different modes of potentially moving a stunned fish past the electric barrier. Concerns about upstream-bound barges are that the bow flow and bow wave may push fish into the electrical barrier to a point at which they become incapacitated. Once incapacitated, the fish may then become entrained into one of the barge-induced flows. If a stunned fish were to remain directly in the path
of the barge until the barge hull physically struck it, the fish may remain entrained in the boundary layer (a layer of static water that moves in the same direction as the vessel [Martin 1997]) that typically forms on the bottom of a barge hull. Also, if a stunned fish were to end up in the wake flow behind the stern of the barge vessel it may remain entrained in that flow. Depending on the amount of accelerated downstream flow though, some fish may be moved further downstream away from the barrier, or stunned fish may end up getting moved back below the barrier after initially being displaced into it. Parker and Finney (2013) found that fish that were struck by barges as far as 100 m below the barriers were still entrained beyond the barriers.

Downstream-bound barges are also a concern because of the net reverse flow that they create (Bhowmik 1991). This flow could potentially move fish into and beyond the barrier. We have noted that Gizzard Shad used in the caged-fish trials quickly recover after becoming incapacitated. Therefore, if a fish that is moved upstream of the barrier recovers while the flow is reversed, it may be able to continue swimming upstream. Of further concern is the low water velocity that typically flows in the CSSC at the barrier site (~0.15-0.3 m/s). This low velocity can take a long time to counteract the barge vessel-induced reverse flow. Also, the CSSC at the barrier site often exhibits no flow or reverses on its own depending on how long the downstream lock and dam structure is closed. We have observed reverse flows at the barrier site for as long as one hour.

We found that once fish started penetrating upstream into the electric barrier, where the electricity would be perceptible, that they were more prevalent along the canal walls, at the water surface. The presence of these fish, which were actively challenging the barrier, at the water surface is not surprising since the electrical field that is first emitted from the narrow barrier arrays (on the bottom of the canal) is approximately 3.54 V/cm (Holliman 2011). We found that caged
fish took longer to become incapacitated when they were moved immediately adjacent to the canal wall through the barrier, indicating that the wall, may be conducting some of the electricity. This may explain why the fish were more prevalent along the canal walls than in the middle of the canal along the bottom. However, we did not assess fish abundance at the water surface in the middle of the canal, therefore we do not know if fish were more prevalent near the walls at the surface or if fish were homogenously distributed along the water surface. Although given the caged-fish results, it seems likely that fish would prefer the wall, since it appears to weaken the electrical field.

Small fish are easily displaced by navigation-induced waves (Holland 1986; Wolter and Arlinghaus 2003; 2004; Kucera-Hirzinger et al. 2008). The effects of navigation-induced waves are attenuated in embayments that are farther away from the main shipping channel or in more complex habitat (Arlinghaus et al. 2002; Gabel et al. 2008). The vertical canal walls of the confined CSSC are the simplest type of bankline that fish could occupy though. These simple banklines cause the greatest amount of hydrologic momentum transfer (Myers 1978), which increases the magnitude and duration of the displacement effects caused by barges. Specific navigation-induced water motions that are more amplified in confined channels, compared to sloped or protected shorelines, include increases in water drawdown, return velocity, transverse stern waves, surge, and scour (Arlinghaus et al. 2002; Maynord 2004; Taylor et al. 2007). Because of the increased magnitude, duration, and velocity of navigation-induced water movement around vertical walls, particle displacement and sediment scour is typically greatest near the bankline (Maynord 1990; Taylor et al. 2007). Therefore, even though the fish that we observed near the canal walls were most likely not at risk of being directly struck by a barge vessel, they could still
be affected by the exaggerated water movements created along the walls. Of particular concern are downstream-bound barge vessels which can create reverse flows (Bhowmik 1991).

Others have shown that fish are indeed entrained by towboats (Gutreuter et al. 2003; Miranda and Killgore 2013), including Bighead and Silver Carp (Killgore et al. 2011). These studies have taken place in large rivers that are very different from the CSSC. Although Killgore et al. (2011) found that at times, fish entrainment was high in narrow sections of water with slow velocity. Indeed, the electrical electric barrier in the CSSC would present a different scenario in which fish encounter a barge vessel than what others have studied. As we have shown, fish accumulate below the electrical barrier. The barrier may act as a “third wall” in the canal system that does not allow fish to escape from oncoming barge vessels, thus making them more susceptible to the barge-induced water movements. Clearly, much is still unknown about fish-barge interactions at electrical barriers, which is why we feel that this is a topic worthy of future investigations.

After the barrier operating parameters were increased from 0.79 to 0.91 V/cm, we found that all fish used in our caged-fish trials were incapacitated, albeit at different distances into the barrier depending on season, fish size, and the type of boat used to move them. Whereas, at the previous parameters, eight fish were not incapacitated. Because, the operating parameters increased soon after we began working at the electric barrier, we do not know how our results would differ with the different settings over an entire year for both the caged-fish and the DIDSON sampling. We were only able to sample the electric barrier during one season (summer) when the operating parameters were at 0.79 V/cm, however, fish accumulation below the barriers was similar at the same time the next year, at the increased parameters. In conclusion, we found that wild fish accumulate below the electric barrier and at times will persistently challenge it.
Some of these fish, depending on their size, were able to penetrate into the barrier as far up as the point of ultimate field strength. Initial results from current work, utilizing two DIDSON units from a fixed platform, revealed numerous instances of schools of small fish breaching the barrier. Of particular concern is when Barrier IIB is de-energized and fish are allowed to move upstream, especially given the reduced operating capacity of the Demonstration Barrier. Also of concern, and the subject of study at the time of this writing is the effects that barges may have on displacing fish across the barriers. As previously stated, it is recommended that any necessary barrier maintenance shut-downs should be performed in the winter as much as possible, and avoided during the summer and fall.

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