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Asian carp movement**

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Abstract: We evaluated the abundance and behavior of wild fish within the electric barrier system in the Chicago Sanitary and Ship Canal. This electric barrier system serves to prevent the upstream migration of bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*) to Lake Michigan from the Illinois River. We found that fish were most abundant below the electric barrier during the summer and fall, were observed near areas of peak voltage, and sometimes persistently challenged the barrier. Fish were relatively scarce within the barrier system during the winter and spring. Fish that were able to penetrate the farthest into the barrier system were smaller and tended to aggregate at the water surface, near the canal walls. The accumulation of fish that we observed below the barrier, and the persistent challenging behavior, raises concerns about breaches any time the barrier is de-energized for maintenance or during intermittent power outages. Entrainment and breach caused by barges traversing the barrier are concerns as well because of the water movements they create and how they alter the electrical field.

Keywords: bighead carp, silver carp, invasive species, navigation, DIDSON

Introduction

Aquatic invasive species are an economic and ecological burden worldwide (Pimental et al. 2005; Williams et al. 2010; Ricciardi and MacIsaac 2011). The Laurentian Great Lakes Basin has a long history of exotic species introductions (Mills et al. 1993; Holeck et al. 2004). Additional, potential invaders of concern, namely bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*), are well established in the connected Mississippi River Basin. These two species are of particular concern to fisheries managers because of their rapid population growth and planktivorous feeding, which increases the likelihood of competition with native larval fishes and adult filter-feeding fish (Schrack et al. 2003; Irons et al. 2007; Cooke and Hill 2010). Modeling efforts have indicated that bighead and silver carps would most likely be able to reproduce in large Great Lakes tributaries (Cudmore et al. 2012; Kocovsky et al. 2012; Murphy and Jackson 2013; Cuddington et al. 2014) and would likely thrive in Lake Erie because of its large algal food base (Anderson et al. 2015).

The Great Lakes and Mississippi River Basins are connected by the Chicago Area Waterways System (CAWS), which is a network of heavily-modified rivers and canals within and surrounding the city of Chicago, Illinois, USA (Fig. 1; described in detail by Moy et al. 2010). In an effort to prevent inter-basin transfer of non-native fishes, an electric barrier system was constructed in the Chicago Sanitary and Ship Canal (CSSC). The original purpose of the electric barrier system, located in Romeoville, Illinois, USA was to prevent the downstream dispersal of round goby (*Neogobius melanostomus*) to the Illinois River from Lake Michigan (Sparks et al. 2010). The first installment of the system was implemented in 2002, post round goby invasion of the Illinois River, which occurred in 1996 (Steingraeber and Thiel 2000; Sparks et al. 2010). Two larger barriers were later added to the system in 2009 and 2011, with the

primary purpose now being to prevent the upstream migration of Asian carps (Moy et al. 2010; Parker et al. 2015).

An electrical barrier was recommended as the best option by the Dispersal Barrier Advisory Panel in 1996 as a non-physical fish barrier in the CSSC based on cost, success likelihood, environmental impact, commercial availability, permit requirements, and effects on existing uses of the CAWS (Moy et al. 2011). The current peak barrier voltage is maintained at 2.5 ms, 30 Hz, 0.91 V/cm (0.91 V/cm), based on intensive laboratory work done by Holliman (2011) on bighead carp that were 46-72 mm TL. Holliman (2011) found that these parameters incapacitated 100% of small bighead carp that were exposed to gradual increases in voltage in a Brett swim tunnel. This voltage setting was inferred to be adequate at preventing upstream migrations of Asian carp, while allowing safe navigation through the barrier. Safety considerations limit the maximum target voltage that the barrier can operate at because numerous barges traverse the barrier with volatile cargo that could explode in the presence of static charges. Currently, strict safety precautions must be followed by barge vessels traversing the barrier such as being tied together with steel cables in order to ground the entire unit (Moy et al. 2011).

The newer barriers in the CSSC cover a much larger area than the first barrier and are capable of generating electrical fields of much higher intensity. 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 (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). Holliman (2011) observed an inverse relationship between the “equipotential boundaries (electrical field strengths that first invoked fish reactions)” and fish size with larger bighead carp repelled further away from the strongest electrical field in a barrier laboratory study. Halsband (1967) attributed the lower response threshold of larger fish to their greater length, which causes them to span a greater electrical potential difference than smaller fish.

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). Currently, aquatic invasive species introductions, coupled with a need to preserve fragile ecosystems have led to increased interest and consideration of electric barriers as management and conservation tools (Noatch and Suski 2012; Rahel 2013; Caffrey et al. 2014). These electric barrier systems are costly both to install and maintain, yet little is known about their long-term effectiveness. In particular, we know relatively little about how fish interact with electric barriers after long-term exposure that could lead to habituation.

Numerous studies exist on the use of electric barriers that are meant to divert fish away from an undesirable area, such as power plant intakes (e.g. Taft 2000). We are not aware of any research, however, that has focused on the abundance, distribution, and behavior of established, wild fish populations that encounter a permanent fish barrier designed to completely stop upstream movements. Previous studies have focused on examining effectiveness of electrical fish barriers in controlled laboratory and field settings (Savino et al. 2001; Dawson et al 2006; Holliman 2011) and at permanent barrier locations in small streams and canals (Swink 1999; Maceina et al. 1999; Clarkson 2004). The electric barrier system in the CSSC is the largest in the

world and is located in an environment that is much different from most systems where smaller barriers have been installed. Furthermore, the CSSC is unlike any other environment where electric barriers operate. Flow in the CSSC varies from complete reversal (towards Lake Michigan) to high velocity “release” events downstream as a result of lock and dam operations, and both recreational and barge vessels regularly traverse the barrier (Sparks et al. 2010; Per. Obs.).

Effectiveness of electrical barriers in controlled laboratory settings have been evaluated via direct observation, but are limited in scope when considering potential acclimation of fishes that continually interact with an electrical field. 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; this indirect approach provides only coarse observations of breaching for fish large enough to mark or tag, relies on imperfect detection probabilities and is unable to assess group behavior. Godlewska et al. (2007) evaluated the abundances of wild fish in front of an electric barrier for a single day using split-beam hydroacoustics, however fish were recorded as “still” images, and behavior could not be directly observed.

The hazardous nature of the barrier system to humans and its location in an active navigation channel preclude the use of traditional fish sampling gear within many parts of it. Because of safety and logistical concerns, SONAR sampling was determined to be the most feasible method to sample the entire gradient of the barrier system. We used dual-frequency identification SONAR (DIDSON; Sound Metrics Corp., Bellevue, WA) that was capable of recording fish movements with near-video-quality, and therefore recorded the fish’s interactions with the electric barrier. The use of DIDSON by fishery scientists to obtain size, behavior, and abundance data is becoming increasingly common (Boswell et al. 2008; Burwen et al. 2010;

Becker et al. 2011). The DIDSON software can process up to seven frames per second, so rather than an acoustic “still” image, DIDSON provides, real-time imaging (Moursund et al. 2003). A DIDSON unit is also capable of capturing consistent images regardless of turbidity and light levels (Moursund et al. 2003), while 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.

By using this technology we were able to easily quantify the real-time interactions of both individual and schooled fish with the barrier and to observe wild fish that were potentially acclimated to the barrier system without the handling stress of being in a laboratory or having a tagging device attached. However, we did not attempt to identify fish species based on the DIDSON images because DIDSON technology is generally not a reliable method for identifying fish targets to species (Mueller et al. 2006). In some cases, species identifications have been correctly made on large fish with unique external shapes such as sturgeon (*Acipenser* spp.; Crossman et al. 2011) and large salmon (*Oncorhynchus* spp.) with unique swimming movements (Burwen et al. 2010) using DIDSON footage. However, small, similarly shaped fish are extremely difficult to accurately identify with any confidence (Becker et al. 2011). Thus, while we were unable to identify sampled fish to species, the use of DIDSON technology allowed us to sample in areas, and observe behavior, within the barrier system that would not have been possible using traditional fish sampling methods.

Holliman (2011) found that when small bighead carp (48-82 mm TL) 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). While these results were concerning, Holliman (2011) noted that the breaches occurred in a controlled laboratory environment and recommended that wild fish populations within the CSSC barrier system be observed to determine if they exhibit similar behavior, which was the goal of this study.

Our specific objectives were to 1) assess seasonal changes in the spatio-temporal distributions of wild fish populations within the entire area of the electric dispersal barrier system throughout a one-year period, 2) assess whether fish size affected fish distributions in various parts of the barrier, and 3) assess fish behavior and the frequency of fish-barrier interactions and behavior within the zone of ultimate field strength.

Materials and methods

Electric barrier system

The power system for the electric barriers is a constant voltage system, meaning that the system automatically compensates for changes in electrical load (water conductivity) to maintain target voltage (Holliman 2011). Furthermore, the barrier output voltage is checked every hour by on-site engineers to ensure the barrier is maintaining a peak target voltage of 0.91 V/cm (Matthew Shanks, USACE, Per. Com.). Independent *in situ* measurements of in-water voltage during 2012 confirmed that the barrier was maintaining its peak target voltage (Per. Obs.; McInerney et al. 2013). Because the electric barrier system operates on a constant voltage system that adjusts to changes in water conductivity and its output voltage is routinely verified, we assumed that the barrier maintained target peak voltage throughout our sampling and did not collect independent in-water voltage data during sampling events.

Fish sampling

Two different sampling methodologies were employed to assess different aspects of wild fish populations within the barrier system: “Standard sampling” sampled fish throughout the entire barrier system (described in detail below) and “focused sampling” only sampled fish within the zone of ultimate field strength (area of peak target voltage). Standard sampling 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. A “sampling period,” in this study, was a three-month, astronomical season (winter, spring, summer, fall). One standard sampling event occurred during each season in 2012. The standard sampling sites were chosen to represent the entire gradient of voltage along the barrier system (see Table 1 for description of sites). In-water voltages begin to rise at the downstream parasitic structure (structure composed of woven wire that “absorbs” and prevents stray electricity from entering areas upstream and downstream of barrier system; 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 barrier system see McInerney et al. (2011)]).

Ten-minute recordings were made at each sub-site in random order. The DIDSON unit was operated in high-frequency mode (i.e., 1.8 MHz) 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 on 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 boat gunwale (Deep Development Corp., Sumas, WA). The DIDSON unit was deployed 1 m below the water surface. The DIDSON unit was held at 0° tilt

(i.e., parallel to the water surface) for sub-sites A and J, -25° tilt for sub-sites B and I, and -45° tilt for sub-sites C-H (Fig. 3). Sampling took place continuously during daylight hours with interruptions occurring only when a vessel passed through the barrier. No recordings were made during vessel passages and sampling typically commenced 15 minutes after a vessel passage. DIDSON sampling performed by Parker et al. (2013) from one fixed location within the barrier system revealed that fish would return to that same location within ten minutes after barge passage.

The focused DIDSON footage fixated on the western wall of the canal within the zone of ultimate field strength, immediately below the water surface. Eighty separate, Ten-minute recordings were made sequentially during each sampling event. Again, the only interruptions were vessel passages, and the DIDSON was operated at the settings described above with the unit fixed at a 0° tilt. Focused sampling only occurred during the spring and summer (April to early September). Two sampling events occurred during the spring sampling period, and two sampling events occurred in the summer sampling period. In the standard sampling method, the focused sampling area would be referred to as Site 6, Section A (Figs. 2 and 3). This site was chosen for focused evaluation because earlier work performing the standard sampling revealed that wild fish were 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 [μ S/cm], and temperature [$^{\circ}$ C]) were recorded once during each DIDSON recording interval (during both standard and focused) 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 10.5 km upstream of the barrier system in the CSSC (http://waterdata.usgs.gov/il/nwis/uv/?site_no=05536890).

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 to best process all data. Individual fish and schools of fish were manually counted. Data were recorded separately for individual and schooled fish because of 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 defined as a singular fish within the DIDSON viewing cone that was not swimming in a similar manner as any nearby fish. Schools of fish were defined as two or more fish swimming similarly nearby each other, and are referred to as schools hereafter.

Total length of fish was measured with the DIDSON software measurement tool (nearest 1 cm). When schools of fish came into the DIDSON view, the lengths of five randomly selected fish were recorded and averaged. Each individual fish or school that entered the DIDSON viewing area was treated separately. 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.

For the focused sampling, we did not count the fish in the same manner as described above. Initially, attempts were made to quantify all fish that appeared in the viewing cone. However, during some sampling events, the entire DIDSON viewing cone would be saturated with a mass of fish moving through it, making the enumeration of separate schools impossible. Further complicating the enumeration of these schools was the behavior and non-directional movement of the fish at the barrier (behavior classifications described below). During some of these times, roughly the same number of fish remained in the viewing cone, although fish could

be observed continuously entering and leaving it. To simplify the estimation of fish occurrence within the zone of ultimate field strength, we only recorded presence or absence of schools and individuals during each ten-minute sample. Those data were then calculated as frequencies of occurrence during each sampling day.

Four different fish behaviors were recorded for the focused sampling: “swimming,” “flight,” “hovering,” and “challenging.” “Swimming” was defined as continuous sustained or prolonged (Blake 1983) movement by the fish in one general direction without any rapid bursts of speed or fast turns. “Flight” was defined as a rapid deviation from normal swimming behavior including burst swimming events of short duration (< 15 s; Blake 1983) that was erratic, non-directional (circling), or included fast turns (Blake 1983; Dettmers et al. 2005; Holliman 2011). “Hovering” was defined as fish maintaining position in one spot for at least five seconds without attempting to swim upstream or downstream. “Challenging” was defined as direct and persistent side-to-side or up and down movement where fish were attempting to swim upstream, however forward progress was either slowed down or inhibited (Holliman 2011). All observed behaviors were recorded for an individual fish and schools of fish. For example, if a fish showed hovering behavior and then challenging behavior, both were recorded.

Data analyses

The probabilities of individual fish and schooled fish presence were compared across locations (i.e., sites or sub-sites) and seasons. 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 sub-site); 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. An odds ratio is the ratio between the probability of an event occurring versus the probability of the event not occurring. An odds ratio of 1 indicates a probability of 0.5 of an event occurring, with greater values indicating a greater probability of an event occurring. 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 sub-site presence of individual or schooled fish within each site, we included both the main effects of site, sub-site, and their interaction. This allowed us to produce graphical plots displaying probabilities of fish presence throughout the barrier system. In all models, beam volume was used as a weighting factor as described below. The effect that fish size has on determining which site a fish was present at was evaluated using a logit model. Wald χ^2 statistics were used to determine whether size had an overall effect on fish distributions throughout the barrier system.

Prior to analysis of count data from the DIDSON recordings, the data were standardized to account for unequal volumes of water that were ensonified by the DIDSON cone. The DIDSON ensonified the same volume of water at all sub-sites with the exceptions of “A” and “J (Fig. 3).” 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 sub-sites A and J received a weighting of 1.11 in all regression models to account for the vertical slice loss; all other sub-sites received a weighting of 1.

Individual and schooled fish presence recorded during the focused recording efforts was assessed as a function of the chemical/physical variables that were recorded during sampling. To evaluate the effect of mean temperature, conductivity, pH, dissolved oxygen, and discharge on fish presence, a principal components analysis (PCA) was used to reduce the dimensionality of the correlated independent variables into a single value, or principal component (PC) score, for each sampling date. Fish presence/absence was assessed as a frequency of the number of samples per sampling day that fish were present. The fish frequency data were arcsine-square-root transformed to create a unimodal distribution and a Pearson correlation was used to assess the relationship between fish frequency and PC 1 scores.

To test whether behavioral responses (i.e., swimming, flight, hovering, and challenging) were more likely to occur in the spring or summer, and whether behavioral responses were more or less likely to occur when fish were observed as schools or individuals, we used binary logistic regression (described above in detail) on data collected from the focused DIDSON sampling near the field of highest electrical strength. Each behavioral response was analyzed separately and models included the main effect of season, and the effect of group behavior (0 = individual fish, 1 = fish school) nested within season. Post-hoc comparisons were conducted to elucidate significant effects. A beam-volume correction was not necessary for these data given that all observations were conducted using the same tilt angle. Significance was judged at an α -level of 0.05 for all comparisons.

Results

The greatest number of individual and schooling fish were observed throughout the barrier system during the summer and fall seasons. The probability of individual fish presence within the barrier system varied across sites and seasons (Table 2). In general, the odds of

individual fish presence across all sites was 5.1 (95% CI = 2.72-9.51) times greater in the fall compared to the summer (Wald $\chi^2 = 25.96$; $df = 1$; $P < 0.001$), but were not different among all other seasons (Wald $\chi^2 \leq 0.001$; $df = 1$; $P \geq 0.974$). Within-season differences in the probability of individual fish presence among sites occurred in the winter, summer, and spring, but were not different in the fall (Fig. 4; Table 3). Probabilities of observing schooled fish at specific sites also differed seasonally, however the main effects of site and season were not significant (Table 2). Probabilistic estimates of fish school presence were different among sites in the summer and fall, but were not statistically different in the winter or spring (Fig. 4; Table 3). Site-specific absences of fish during the winter and spring precluded all possible comparisons among sites. Both the individual and schooled fish were largely absent from sites 4-6 during the winter and spring periods. However, fish began to penetrate farther into the barriers in the summer and fall, with both individual and schooled fish observed as far into the barrier as site six (Fig. S1), which contains the ultimate field strength.

We found that schooled fish exhibited differential use of sub-sites across seasons (Wald $\chi^2 = 45.82$, $df = 27$, $P = 0.013$) as did individual fish (Wald $\chi^2 = 55.65$, $df = 27$, $P = 0.001$). Probabilities of schooled fish presence differed among sub-sites in the winter and fall, but not in the spring or summer and individual fish presence showed similar seasonal patterns (Table 3; Fig. 5). Within-season probabilities of individual fish presence differed among sub-sites in the winter and fall, but were not different in the spring or summer. Within sites 1-3 and site 8, both individual fish and schools of fish utilized the majority of the sub-sites across the width of the canal. 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 (Fig. 5).

We found that the presence of individual fish at specific sites was related to fish size during the fall (Fig. 6; Wald $\chi^2 = 18.45$, $df = 7$, $P = 0.010$) and in the summer for schooled fish (Fig. 6; Wald $\chi^2 = 33.20$, $df = 6$, $P < 0.0001$), but size did not have an effect in other seasons for individuals or schools. Larger fish (> 30 cm TL) had the greatest probability of being present at sites 1-3. At sites 4-8, small fish had higher probabilities of being present.

The PCA of the chemical/physical data recorded during the focused fish sampling revealed a temperature-pH-discharge-conductivity gradient along the first principal component (49% variability explained), and a weaker dissolved oxygen gradient along the second principal component (32% variability explained; Fig. S2). Pearson correlations revealed a significant negative relationship between individual ($R^2 = -0.83$; $P < 0.0001$; Fig. S3B) and schooled ($R^2 = -0.94$; $P < 0.0001$; Fig. S3A) fish frequencies and PC 1 scores. High temperatures and increased discharges were associated with low PC 1 scores, which corresponded to higher frequencies of fish detection.

During our focused DIDSON sampling we recorded 23 separate behaviors from 16 individual fish during the spring and 111 behavioral observations from 92 individuals during the summer. Swimming was the most frequent behavior observed by individual fish in both seasons, yet the probability of observing individual fish swimming was 50% more likely during the summer than the spring ($z = 2.19$; $P = 0.029$). Flight, hovering, and challenging behaviors of individual fish were observed in approximately equal frequency during the spring, but challenging behavior occurred more frequently during the summer (16 instances in the summer vs 4 instances in the spring). Differences in the probability of these behaviors occurring, however, was not different between seasons for challenging ($z = 0.72$; $P = 0.472$) or flight ($z = 1.03$; $P = 0.301$; Fig. S4A); hovering was observed only in the spring.

We recorded only one fish school during the spring (observed swimming) and 219 behaviors from 157 schools during the summer. The single observation of schooled fish during the spring precluded comparisons between seasons or individual fish. Nevertheless, the behavior most frequently observed by schooled fish during the summer was swimming ($n = 136$) and challenging behavior was the second most common behavior ($n = 77$). When compared to individuals, schooled fish were 4.6 times more likely (95% C.I. = 2.45-8.53) to exhibit challenging behavior during the summer than individual fish ($z = 4.78$; $P < 0.0001$). Schooled fish were also 2.1 times more likely (95% C.I.s = 1.77-39.80) to exhibit flight behavior than individual fish during the summer ($z = 2.68$; $P = 0.0073$; Fig. S4B). Schooled fish were no more likely to be observed swimming ($z = 1.64$; $P = 0.10$) or hovering ($z = 0.06$; $P = 0.95$) compared to individual fish during the summer.

Both individuals and schools of fish that challenged the barrier were observed facing upstream and swimming both up and down and sideways along the electrical field; fish were also observed swimming into the electrical field and then returning downstream on their own volition. We did not observe any fish becoming incapacitated within the barrier. The fish that were observed penetrating the furthest upstream into the zone of ultimate field strength attempted to move farther 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 (Holliman 2011).

DIDSON cannot effectively be used for small fish species identification, and therefore was not an objective of our study. However, electroshocking in 2012 concurrent with DIDSON sampling in an early study (ACRCC 2013) found that 73% of the 4408 fish collected were gizzard shad (*Dorosoma cepedianum*), 9% were emerald shiner (*Notropis atherinoides*), and 5%

were green sunfish (*Lepomis cyanellus*). Based on this sampling using traditional gear, as well as personal observations, the majority of small fish that we observed persistently challenging the barrier were likely gizzard shad.

Discussion

We found that at times, wild fish will accumulate in large numbers downstream of the electric dispersal barrier system. During these times, we observed that fish were not repelled by the barrier, but rather, often persistently challenged it. The accumulation of fish downstream of 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 wild fish continuously challenging the barrier are consistent with other findings of fish repeatedly challenging an electrical barrier in experimental settings (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 electric barriers should be used to modify a particular fish behavior rather than outright prevent it.

On several occasions, we observed fish swimming through the entire DIDSON viewing cone that was ensonifying the area within the zone of ultimate field strength (where the electrical voltage is highest). 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 full length of the barrier by swimming all the way through it. However, in the summer of 2013, we utilized two fixed-position, DIDSON units that simultaneously recorded the entire width of the ultimate field strength zone. With these units, we

recorded numerous instances in which schools of small, wild fish breached the barrier (Parker et al. 2013).

Both our standard and focused DIDSON sampling revealed that fish were most abundant within the barrier system during the summer and fall, at which time they most actively challenged the barriers. During the winter and spring, very few fish were present near the barriers, and fish were not present in the zone of ultimate field strength. We observed no differences amongst individual fish abundance throughout the barrier in the fall, implying that, compared to other seasons, the barrier was essentially ineffective at controlling individual fish distributions. The distributions of fish schools during the fall were not homogenous, but differences between sub-sites within the zone of ultimate field strength, and between sites with low/no voltage became less distinct than in other seasons.

The homogenous distribution of individual fish in the fall could be attributed to fish more actively probing all areas of the barrier, searching for areas of weakness, whereas the schooled fish may possibly have located the weakest areas of the barrier and were challenging it. Holliman (2011) found that schools of small bighead carp were more likely to challenge a laboratory barrier than individual fish. Also, during separate DIDSON work at the barrier system, we observed numerous breaches of the barrier by schools of small fish at the zone of ultimate field strength (Parker et al. 2013). However, individual and even loosely aggregated fish were unable to breach the barrier (Parker et al. 2013).

We found that throughout most of the early summer, fish were accumulated below the barrier and evenly distributed across the width of the canal, suggesting that they may have been swimming back and forth, probing the barrier, but not actively challenging it as much. However, in the late summer when water temperatures were at their peak, fish were observed more actively

challenging the barrier near the canal walls, at the water surface. This may be because the barrier voltage is weakest at the water surface near the canal walls (Holliman 2011). The results of separate work performed by us in which live, caged gizzard shad were moved through the barriers, revealed that the fish always took slightly longer to become incapacitated when moved along the canal wall compared to the mid-channel (Parker et al. 2015). Parker et al. (2013) also observed that when fish breached the barrier, they often did so at the water surface adjacent to the canal wall.

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 furthest. Mostly larger fish were present in the winter and spring, with the smallest individuals likely age-1 fish from the previous year. Seasonal recruitment of age-0 fish to the canal in the summer and fall resulted in the greatest barrier penetration. The phenomenon of water-borne electricity affecting larger fish more than smaller fish has been well-established based on electrofishing studies (e.g. Reynolds 1996). Holliman (2011) also found that smaller bighead carp were able to penetrate farther into a laboratory-electrical barrier before movement was either inhibited or a breach occurred.

Based on these results and other work (Holliman 2011; Parker et al. 2013), the barrier appears to be most susceptible to breach by smaller fish. Larger fish (> 30 cm TL) were mostly restricted to an area about 80 m below the zone of ultimate field strength. Therefore, the biggest concern for barrier breach by larger fish would be when the barrier is de-energized. Holliman (2011) observed that juvenile bighead carp “immediately” swam upstream in a flume system after a barrier was de-energized. Therefore the risk of breach would depend on how long the barrier was de-energized. The swimming speeds of adult Asian carp are unknown, however,

Hoover et al. (2012) measured swimming speeds on sub-adult bighead and silver carps (141-334 mm TL) and predicted prolonged (1 min) swimming speeds of 1.1 and 0.7 m/s and sustained (200 min) swimming speeds of 0.8 and 0.5 m/s for bighead and silver carp respectively. Based on these speeds, if the barrier were to be de-energized for more than 1 min with large Asian carp present, there would be a high risk of breach.

During our focused sampling, we observed numerous instances of large schools of fish repeatedly challenging the barrier. We found that a combination of high water temperatures coupled with slightly increased canal flows explained the high amount of resident CSSC fish present at the barrier and challenging it; the negative correlation with conductivity, however, is likely spurious since there is an inverse relationship between temperature and conductivity in the CSSC as a result of heavy winter road salt application in the city of Chicago (Holliman 2011).

These results suggest that the barrier is least susceptible to breach during the winter and spring. In the summer and fall, however, the barrier appears particularly susceptible to breach because of the greater abundance of fish present at the barrier, especially smaller ones, and their increased activity levels. The summer is also when barge traffic is at its peak. Others have found that metal hull boats and barges are capable of distorting the barrier electricity to the point that fish can swim farther into the barrier on their own volition or be entrained beyond the barrier (Dettmers et al. 2005; Parker and Finney 2013; Parker et al. 2015). Because of the high conductance of large metal barges, the barrier electricity is strongly attracted to the metal and is largely withdrawn from the water as it circulates through the barge. *In situ* measurements of in-water voltages along numerous locations adjacent to a barge traversing the CSSC barrier have revealed that peak in-water voltage can be reduced to as low as 0.06 V/cm (normal peak voltage is 0.91 V/cm) in certain areas adjacent to the vessel (Parker and Finney 2013; Per. Obs.).

The observed increased activity and movement of the fish at the barrier is to be expected of temperate zone fishes during warmer weather (e.g. Gauthreaux 1980). Because of the increased activity and fish movement during warmer weather, we feel that any barrier maintenance shut-downs should be performed in the winter and spring to the extent possible (at least once per year, electrical and mechanical components of the barrier must be inspected and cleaned; to ensure the safety of inspectors, the barrier must be de-energized [Matthew Shanks, USACE-Chicago, per. Comm.]).

Based on these results, the presence of Asian carp below the barrier would be concerning. 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). Others have observed that fish will swim upstream of a barrier soon after it is de-energized (Stewart 1981; Swink 1999; Godlewska et al. 2007) including bighead carp (Holliman 2011). Recent modeling results by Cuddington et al. (2014) indicated that given a scenario in which Asian carp containment was “continually leaky” that even a small number of individuals entering the Great Lakes could potentially establish a reproducing population.

We acknowledge that fish behavior around electric barriers likely differs depending on species and even within species, depending on ontogenetic stage. However, wild fish within the CSSC barrier system exhibited the same general behaviors as bighead carp in laboratory experiments (Holliman 2011), where small bighead carp continuously challenged a laboratory barrier and breached it at voltage settings equivalent to that in the CSSC (0.91 V/cm). We found that wild fish in the CSSC do indeed persistently challenge the barrier in the same manner that the bighead carp did in Holliman’s (2011) experimental work, and that this persistent challenging behavior resulted in fish breaching the CSSC barrier (Parker et al. 2013).

The current upstream extent of small Asian carp (< 200 mm TL) in the Illinois River, which would pose the greatest threat to barrier breach, has been documented about 64 km below the barriers (R. Neeley, USFWS, Per. Obs.). Adult Asian carp are currently captured on a regular basis in a small lake connected to the Des Plaines River, below where the CSSC enters it, 23.5 river km below the electric barriers (USFWS 2014). 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 barriers (Moy et al. 2011). Also, environmental DNA (eDNA) of both bighead and silver carps has been detected above the barrier system in the CAWS (Mahon et al. 2013). The capture of live Asian carp above and immediately below the barrier system, as well as the continued presence of eDNA above the barriers, has led some to contend that a small population of Asian carp reside in the CAWS (Rasmussen et al. 2011; Jerde et al. 2011).

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 that covers the full width of the canal, revealed numerous instances of schools of small fish breaching the barrier (Parker et al. 2013). Of particular concern are times when barriers are de-energized, as part of either planned maintenance or unpredicted power failures, and the effects that barges may have on displacing fish across the barriers. Our observation of peak barrier challenges in the summer and fall indicates that any barrier maintenance shut-downs should be performed in the winter and spring as much as possible. This study highlights important considerations about fish behavior and

interactions with electric barriers that should be considered by fisheries managers when contemplating costly barrier systems as a management strategy.

Acknowledgements

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Table 1. Description of DIDSON recording sites.

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

Table 2. Wald χ^2 test statistics for site, season, and site $\times$ season interaction effects.

Effect	Individual fish		Schooled fish	
	Wald χ^2	df	Wald χ^2	df
Site	18.75*	7	0.0004	7
Season	25.96*	3	0.004	3
Site $\times$ season interaction	39.77*	21	60.59*	21

* $P < 0.05$

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Table 3. Wald χ^2 test statistics for seasonal site and sub-site fish presence probabilities for individual and schooled fish.

Season	Site presence probability						Sub-site presence probabilities			
	Individual fish			Schooled fish			Individual fish		Schooled fish	
	<i>n</i>	Wald χ^2	df	<i>n</i>	Wald χ^2	df	Wald χ^2	df	Wald χ^2	df
Winter	74	22.47*	7	46	4.47	7	41.10*	9	19.70*	9
Spring	41	18.21*	7	46	8.90	7	10.46	9	12.18	9
Summer	45	22.12*	7	215	37.94*	7	10.03	9	11.00	9
Fall	123	11.77	7	246	31.42*	7	20.65*	9	28.47*	9

**P* < 0.05

Fig. 1. Chicago Area Waterway System, important tributaries and canals as well as the location of electrical barriers indicated by the black diamond. CR = Calumet River, C-S C = Cal.-Sag Canal, Ch. R = Chicago River, CSSC = Chicago Sanitary and Ship Canal, DPR = Des Plaines River, GCR = Grand Calumet River, LCR = Little Calumet River, NSC = North Shore Canal.

Fig. 2. Schematic of the barrier system 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.

Fig. 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.

Fig. 4. Season-specific probabilities of individual and schooled fish presence at sites 1-8 within the electric dispersal barrier throughout 2012 (pooled across sub-sites). Bars with similar letters indicate statistically similar odds ratio estimates between sites within a season ($P > 0.05$). An asterisks (*) indicates that fish were never observed at these sites such that no valid comparisons were possible.

Fig. 5. Season-specific probabilities of individual and schooled fish presence at sub-sites A-J within the electric dispersal barrier throughout 2012 (pooled across sites). Bars with similar letters indicate statistically similar odds ratio estimates between sub-sites within a season ($P > 0.05$). An asterisks (*) indicates that fish were never observed at these sub-sites such that no valid comparisons were possible.

Fig. 6. Probability models for fall season, individual fish and 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, summer
schooled fish because no fish schools were present at that time.

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Fig. 2.

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Supplementary material

Fig. S1. Probabilistic estimates of individual and schooled fish presence plotted across sites and sub-sites 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 sub-site probabilistic estimates to be either 0 or 1.

Fig. S2. Principal components analysis bi-plot of five continuous variables measured during focused fish sampling in the zone of ultimate field strength. Arrows represent eigenvectors multiplied by five to scale to bi-plot area. TEMP = temperature ($^{\circ}\text{C}$), Q = canal discharge (m^3/s), D.O. = dissolved oxygen (mg/l), and SPC = specific conductance (mS/cm). Diamonds ($\blacklozenge$) represent samples taken in April, squares ($\blacksquare$) represent samples taken in May, triangles ($\blacktriangle$) represent samples taken in July, and circles ($\bullet$) represent samples taken in September.

Fig. S3. Linear regressions of principal component 1 scores versus individual (A) and schooled (B) fish frequencies. Diamonds ($\blacklozenge$) represent samples taken in April, squares ($\blacksquare$) represent samples taken in May, triangles ($\blacktriangle$) represent samples taken in July, and circles ($\bullet$) represent samples taken in September.

Fig. S4. Probability of occurrence for different behaviors observed by individual (white bars) and schooled fish (gray bars) during the spring (A) and summer (B) focused sampling at the zone of ultimate field strength in the barrier.

Fig. S1

Fig. S2.

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Fig. S4.