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Final Report: Integrating detection, deterrents, and operations at Upper Mississippi River navigation lock and dams

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EXECUTIVE SUMMARY

This project had two subprojects, each of which examined different ways that locks and dams can be used to reduce the upstream movement of Bigheaded Carp into Minnesota waters at low cost. If movement can be impeded enough it is possible that there may never be enough Carp to reproduce successfully or if there are they can be easily removed. In the first subproject, passage rates of fish through a lock and dam were monitored to determine fish passage rates through its spillway gates, and how they might be explained by water velocities calculated by a computational fish passage model (FPM). We found that fish passage rates through the spillway gates of Lock and Dam 2 were low for three field seasons and only occurred when the gates were fully open, as predicted by our FPM, meaning that this model can be used to guide large reductions in carp movement elsewhere. In the second subproject, Common Carp passage through a lock equipped with an underwater sound system that played a low amplitude outboard motor sound was studied. We found that these fish were not deterred by this particular sound. In conclusion, while spillway gate passage probably can now be predicted by our FPM, allowing it to be used in Bigheaded Carp control, more effective types of sound such as the cyclic sound used in a bioacoustics fence (Fish Guidance Systems Ltd.) should be considered to block Carp passage through locks.

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PROJECT ABSTRACT

Silver (*Hypophthalmichthys molitrix*) and Bigheaded Carp (*H. nobilis*), together known as Bigheaded Carps, are reproducing in the Mississippi River approximately 200 km south of the Minnesota border and threaten to invade Minnesota. The Sorensen research team has hypothesized that this invasion might be dramatically slowed at key lock and dams by rebalancing and enhancing water velocities flowing through spillway gates to create fast uniform velocities, while adding acoustic deterrents to their lock chambers. Should invasion rates be slowed enough it is possible these Carp may not reach the densities needed to reproduce successfully or if they do, they could be easily removed. This study tested this scheme by: 1) describing fish passage rates and approach behaviors through a key lock and dam (Lock and Dam 2) to determine if it was consistent with water velocities and swimming performance as measured by a computational fish passage model (FPM); and 2) monitoring fish passage rates through the lock chamber of Lock and Dam 8 which was equipped with a relatively simple low volume speaker system which broadcast the complex sound produced by an outboard motor.

To address our first objective, we deployed an acoustical tracking array around Lock and Dam 2 (LD2) for three field seasons and then compared passage rates and paths with those predicted by our FPM at this structure for the observed river conditions. Four species of fish were captured, tagged, and released below LD2 (Pool 3) or captured above LD2 (Pool 2) and released below LD2 (Pool 3) after being equipped with dual acoustic/radio tags. A total of 112 tagged Common Carp (*Cyprinus carpio)* were released, of which 29 (26%) passed through LD2 with only 7 (6%) passing through the spillways gates, with the vast majority (90%) passing during open river conditions which occurred

for 5 days in 2018. Thirty-one Channel Catfish (*Ictalurus punctatus*) were also tagged and released with 17 (55%) moving upstream through the Lock and Dam, of which only 1 (3%) went through the spillway gates, again only during open river conditions. Of 21 tagged Bigmouth Buffalo (*Ictiobus cyprinellus)*, 5 (24%) passed upstream through the lock and dam, including two through the spillway gates during open river conditions. Finally, of 22 Walleye (*Sander vitreus*), 3 (14%) passed through the lock and none (0) passed through the spillway gates. These passage rates matched FPM predictions which, it now seems, could be used to identify specific LDs and spillway gate operations that could impede carp passage. Prior to passage, we also observed many fish using low velocity areas along the sides of the river and seemed to frequent the river edges below this structure, in seemingly species-characteristic manners that could possibly be exploited in carp control or perhaps help pass native fish by opening certain spillways gates in certain ways and times.

To address our second objective on complex sound deterrents, 8 groups of 20 adult Common Carp were captured above Lock and Dam 8 (LD8) and moved below it, where they were acoustically tagged and tracked via a passive acoustic array as they approached a custom-made acoustic deterrent system that had been mounted to the lock chamber gates in 2011. When activated this acoustic deterrent which broadcast a 500-1500hz outboard motor sound at approximately 140db which was activated when the lock gates were opened. The system was activated for 2 week periods and deactivated for alternating 2 week periods. Of the 8 groups of Common Carp, 4 were released and monitored while the sound was on while the other 4 groups were released and monitored with the sound off. Each group was monitored for 14 consecutive days. A total of 14 Common Carp passed upstream through the lock chamber, 8 when the sound was on and 6 when it was off. There was no significant difference in the rate of entrance/passage between sound off and sound on (p-value >0.05), suggesting that this sound played in this manner did not affect Common Carp passage. Additionally, we monitored the presence of fish in front of the lock doors using an ARIS sonar system when the sound was on vs off and again no difference was observed (p-value >0.05). This is the first study that we know of that tested an acoustic deterrent system on navigational lock gates, and while it was ineffective, we now know of much better acoustic deterrent systems, such as the bioacoustic fence (BAFF) that now warrants testing. If such a system were found to be effective, it could be employed with spillway gate adjustments (as determined by our FPM) and combined with other tools (e.g., physical removal) at key locations to greatly reduce carp passage as part of integrated control program.

1.0 INTRODUCTION TO THE BIGHEADED CARP PROBLEM AND THIS REPORT

Silver Carp (*Hypopthalmichthys molitrix*), Bigheaded Carp (*H. nobilis*), Grass Carp (*Ctenopharyngodon idella*) and Black Carp (*Mylopharyngodon piceus*) were introduced to Arkansas from China in the 1970's (Kolar et al. 2005). All four species of "Asian Carp" spread from their points of introduction within a few years and quickly established self-sustaining populations, which complimented the already abundant Common Carp (*Cyprinus carpio*) that had been introduced a century before. The Silver and Bigheaded Carp, collectively known as "Bigheaded Carps" (*Hypopthalmichthys sp*.) have been spreading ever since and have come to comprise up to 75% of fish biomass in the middle Mississippi River and its tributaries including the Illinois River (Tucker et al. 1996; Kolar et al. 2005). Both Bigheaded Carps are microphagous and alter ecosystems by outcompeting native planktivores including Paddlefish (*Polydon spathula*), Bigmouth Buffalo (*Ictiobus cyprinellus*), and Gizzard Shad (*Dorosoma cepedianum*), altering food webs (Schrank et al. 2003; Irons et al. 2007; Sampson et al. 2009; Sass et al. 2014). Silver Carp also threaten human safety because of their habit of jumping (Buck et al. 2010). Both Silver and Bigheaded Carp have established reproducing population between Pool 14 and Pool 16, just south of Minnesota (Larson et al., 2017). Any safe means that might deter their spread north is thus of interest, particularly part of an integrated control program that could include targeted removal.

The Sorensen laboratory at the University of Minnesota has been pursuing the possibility that Mississippi River lock and dams already greatly reduce upstream migration of Bigheaded Carp (and other fish) because of the high flow velocities that pass through their gated spillway dams. This attribute (i.e., the water velocity field as determined by gate opening) could be further enhanced by relatively simple changes in gate operations to balance flows so there are no slow regions. Such a scheme should be acceptable to the US Army Corps of Engineers (USACE) as it also reduces scour. While a total block in Bigheaded Carp passage may never be possible, a reduction in passage rates is still of great interest because by reducing carp numbers it both reduces the risk of Carp reproducing successfully and/or facilitates possible carp removal while coming at no cost. Recent multistate modeling suggests this approach has promise in upper sections of rivers (Coultier et al. 2018). Native fish movement (which is also affected by gate operations) might even be helped with a greater understanding of how and when passage occurs (or not) at certain locations because there is the opportunity to adjust spillway gate openings based on individual fish swimming performance and behavior.

Recently a computational fish passage model (FPM) (Zielinski et al. 2018) was created that determines velocity fields under spillway gates of lock and dams, and then calculates whether this might allow certain species and sizes of fish to pass based on their swimming performance. Importantly, this FPM (which is based solely on fish physiological swimming performance) also has the ability to evaluate how fish passage rates might be reduced by adjusting gate openings in ways that also address vessel navigation and scour. This model could be used at any lock and dam, but clearly has greater utility for those locations which rarely experience “open river” conditions, when the river goes into flood stage and spillway gates must be fully opened. However, some lock and dams (ex., #2, #4, #5) rarely go into open river and are therefore of special interest and their operating schedules might be most easily changed with the potential for high payback. The FPM is solely based on the physiological swimming capabilities of fish and does not presently consider any behavior other than assuming fish likely choose the most energetically efficient path to swim upstream. Further is necessarily calculates a passage index (estimate of the likelihood of passing give a set number of attempts) but not a rate (to do this would require behavioral information). It is thought to overestimate relative passage because of its reliance on fish swimming performance but this has not been tested. Of course, if fish passage can be substantially reduced (or enhanced for native fish above choke points) in well-understood and controllable manners, then sensory deterrents such as sound could be added to locks to stop Bigheaded Carp, as these fish (like other ostariophysians) have an extremely sensitive sense of hearing.

A key aim of the present study was to test the FPM for the first time to determine if it could be used to selectively reduce carp passage at certain locks and dams and gates within them, thereby assisting in carp control and native fish management. We chose to test it at Lock and Dam 2 (LD2) which is located upstream of the St. Croix River confluence and differs from other Upper Mississippi River lock and dams because it lacks a continuous downstream erosion protection structure (i.e. stilling basin). As a result, its gates (which are all tainter gates) are operated as groups of 3-to-4, each of which is opened to different heights as the river discharge increases, creating four distinct velocity regions that could be monitored. Notably, this structure rarely goes into open river, making it an ideal study site. We were primarily interested in whether, how, and when various species pass through the spillway gates of this structure, and its relationship to water velocities and fish swimming performance as used by the FPM. In particular, we were interested testing whether the FPM overestimates or underestimates relative fish passage. Notably, fish swimming performance (the physiological ability of fish to swim against velocities for set periods of time before exhausting), has only been studied in few large river fishes at the present time, but the carps are in this group (Hoover et al. 2016).

While each lock and dam has the tendency/ability to limit fish passage in a species-specific and situation-specific manner through its spillway gates, each structure also possesses a navigation lock which, when in use, might also allow fish passage. Many researchers have proposed that sound deterrents might be added to the locks to prevent invasive carp from passing through these much smaller structures. Sound is of special interest because carps, like all ostariophysians, have a Weberian apparatus that makes their sense of hearing much more sensitive to particular sounds (frequencies above 1000hz in particular; Lovell et al. 2005, 2006; Popper and Carlson 1998; Popper 1972). Laboratory tests show that sound is repulsive to Common Carp but not Sturgeon (Zielinski and Sorensen, 2016; Vetter et al. 2015) but this possibility has not yet been tested in front of an active lock chamber. This project also tested a sound system mounted on the navigational lock gates at LD8 which emits a simple outboard motor sound when its gates open, to determine its efficacy to deter carp.

The contract for this 3-year project had 4 deliverables (excluding this final report) which we address in this report using the terms and specific wording described in that original contract. It is important to appreciate that after discussions with the DNR, we reached an agreement that this report should focus on developing manuscripts for publication in peer-reviewed journals (for wide dissemination and a high level of review). Its structure follows that request with the work conducted for the first study on fish passage at LD2 being presented as three draft manuscripts. The first is on passage and is currently in review by the journal of *River Research and Applications*. The second on fish behavior below the lock and dam and is much less developed at this time and not yet targeted for a particular journal. It is intended to inform future FPM by providing needed behavioral information. The third manuscript describes our study at LD8 on an acoustic deterrent and is written in the style of the *North American Journal of Fisheries Management.* Following the styles of the target journals, they are relatively short as the manuscripts follow the journal's required word limit, while focusing strongly on the higher quality data. Thus, this final report does not attempt to comprehensively review all data collected, nor does it provide fully developed context for the studies, nor does it attempt to describe recommendations for state-wide invasive (Asian and Common) carp control programs that the DNR might run or possible research directions. Nevertheless, we trust it will be helpful in developing such programs.

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2.0 DELIVERABLE #1 for DNR (from original contract). Coordinating with the Minnesota DNR and other partners by holding annual workshops, which includes a kick-off meeting.

We met with the MN DNR fisheries staff before both the 2017 and 2018 field seasons to discuss our results and sampling plans. We gave three presentations on our study at the Minnesota American Fisheries Society meeting (posters in 2017 and 2018, 2 talks in 2017), which many key personnel attended. A presentation was given at the MN DNR fisheries research meeting in the summer of 2017. A presentation was also given at the Stop Carp Forum in Bloomington, MN in 2018. Additionally, we worked with the MN DNR to obtain sampling permits and we emailed them weekly updates on our sampling plans throughout this project. We have also been communicating with the WI DNR, who issued us sampling permits for our work at LD8 and have been very helpful. The USFWS is also a partner in the LD8 portion of this project and knows of our results via many meetings.

3.0 DELIVERABLE #2. Monitoring the specific tendencies of several native fishes and Common Carp to swim into and through specific flow-fields below specific sets of spillway gates of a model lock and dam(s) (Lock and Dam 2 is our preferred site for year 1) under different operating conditions to determine whether the fish passage model is performing correctly and might be used to develop deterrent flows in other lock and dam structures (Objective #1).

3.1 INTRODUCTION AND SYNOPSIS FOR DELIVERABLE #2

Between August 2016 and August 2018 we captured, tagged, released and then tracked nearly 200 fish in the vicinity of Lock and Dam 2 (LD2). As proposed in the contract, we used tags with both acoustic and radio capabilities and tracked tagged fish (Common Carp, Channel Catfish, Bigmouth Buffalo, Walleye) using both archival receivers mounted on LD2 and manually using a boat. Fish were captured either below (Pool 3) or above (Pool 2) LD2 but all were tagged and released in Pool 3. We now have the first definitive dataset on fish passage rates through a lock and dam in the upper Mississippi and in Minnesota waters. Briefly, these data show several things. First, they show that relatively few fish are able to pass through the spillway gates at LD2 and those that do, do so during open river conditions (when the gates are fully out of the water), as predicted by the computational fish passage model (FPM). Because gates are rarely in open water conditions at many (but not all) locks and dams (ex. Lock and Dam 2 was in open river for only 5 days in 3 years), locks and dams could be used to greatly delay Carp movement upstream, perhaps with the help of the FPM which can provide guidance on how to further delay passage (and which now appears to be correct). Second, notable passage rates were observed through the lock with species differences being evident, therefore sound deterrents deployed at lock entrances could be expected to have an impact on the upstream movement of fishes. Third, we found clear evidence that Common Carp and Channel Catfish display homing tendencies when displaced. Finally, manually tracking data showed that fish frequently use the sides of the river where flows are slowest and approached the Lock and Dam 2 multiple days, strongly suggesting they challenge this structure, and when the gates were fully opened (placed in open river), can pass immediately.

The study was complicated by the fact that radio and acoustic signals proved more difficult to detect and track than we had originally thought. In particular, radio signals were masked by electrical noise (i.e., interference from other sources) around the dam structure and (as expected) did not work below 4 meters in depth. In addition, we discovered the acoustic signals were not consistently detectable in highly turbulent waters. Further, because of concerns about catching and moving fish during times of high water temperatures, we necessarily focused on Common Carp (which was also the only species that we were able to easily catch that had reasonable fish swimming performance data). Lastly, we experienced problems with the archival receivers, which on several occasions failed to store data but which we usually could compensate for by using proximate receivers. The end result is that we have relatively high quality data on passage rates from the acoustical data and lower-quality but still valuable (one of a kind) descriptive data on fish behavior in the vicinity of a lock and dam. These two data sets (fish passage and behavior) were analyzed separately for this report, along with data on tag performance. Each are described in different sections below. The fish passage data was written up as a draft manuscript for the journal of *River Research and Applications* where a version closely resembling the one found below is presently under review as of March 12, 2019 (submission Dec 20, 2018). Articles in this journal cannot be longer than 6000 words so it is relatively short. Authors are Finger, Riesgraf, Zielinski, and Sorensen. We ask that readers contact Sorensen about the status of this manuscript before referencing it to prevent confusion.

3.2 DRAFT MANUSCRIPT ON FISH PASSAGE (under review) written for *River Research and Applications*: Monitoring upstream fish passage through a Mississippi River lock and dam reveals species differences in lock chamber usage and supports a fish passage model which describes velocity-dependent passage through spillway gates

3.2.1 ABSTRACT

Approximately 200 fish were released below Lock and Dam 2 (LD2) in the Upper Mississippi River and tracked to determine both whether and how they passed through this structure, and if passage could be explained using a computational fish passage model (FPM) which combines hydraulics with fish swimming performance. Fish were either captured and released downstream of LD2 in Pool 3 or captured in Pool 2 (upstream of LD2) and displaced below LD2. Tagged fish were then tracked using 13 archival receivers located across LD2. Approximately 90% of all fish approached LD2 at least once with the displaced species likely attempting to home. Of 112 Common Carp, 26% passed through LD2 with 15% (most) going through the lock, and 6% through the spillway gates. Similar values were seen for Bigmouth Buffalo. In contrast, while 42% of 31 Channel Catfish passed through the lock, only 3% went through the gates. Finally, of 22 Walleye, only 14% passed through the lock and none through the gates. Ninety percent of all documented passages through the spillway gates occurred when the gates were out of the water (open river) and water velocities their lowest, an attribute described and predicted by the FPM. This study suggests that fish passage through spillway gates of LDs is determined by water velocity and can be predicted with a FPM, while passage through locks is determined by species-specific behavioral preferences. Both attributes could be exploited to permit passage of desired native fish and block passage of invasive carp.

Keywords: Displaced, fish passage model, invasive, lock chamber, open-river, spillway gates, swimming performance

3.2.2 INTRODUCTION

Nearly all rivers worldwide are now regulated by dams whose modified flows seem to impede the natural movement of the many species of migratory fishes typically found living in these systems (Dynesius & Nilsson, 1994). Among the different types of dams, locks and dams (LDs) which combine navigational locks with gated spillway dams to create water depths suitable for navigation are of special concern because they are commonly used in large shallow rivers such as the Mississippi River. Although it is now well established that LDs impede the natural movement of river fishes (Argent & Kimmel, 2011; Liermann, Nilsson, Robertson, & Ng, 2012; Poff, Olden, Merritt, & Pepin, 2007), the extent to which this occurs and its reasons are still not well understood. This situation has recently garnered attention in the Mississippi River where LDs appear to be blocking upstream movement of invasive Silver Carp, *Hypophthalmichthys molitrix,* and Bigheaded Carp, *H, nobilis*, which were introduced in the 1970’s (Kolar et al., 2005; Lubejko et al., 2017; Tripp, Brooks, Herzog, & Garvey, 2014).

Lock and dams (LDs) offer two pathways for upstream moving fishes: their navigation locks and their spillway gates. While passage through navigational locks is regulated by miter gates which open with boat traffic, possible passage through spillway gates is likely affected by the water velocities passing through them, which are determined by gate openings (operating conditions) and water levels. Water velocities below spillway gates are strongest during times of low flow when gates are lowered to pass less water, and weakest when flows are high and gates are lifted out of the water, a condition known as “open river.” While it is commonly hypothesized that water velocities (and gate openings) determine fish passage rates, this hypothesis has not yet been tested directly because biologists have, to-date, been unable to pair an understanding of hydraulics with fish swimming performance and behavior. Complicating this scenario is the fact the water velocities vary greatly with individual LD structures, operating conditions and river flow, while fish swimming performance (the relationship between how long/far fish swim at different speeds) varies by species, length, and environmental conditions. Nevertheless, several descriptive tracking studies do suggest that many fishes are routinely blocked by spillway gate flows. In a study of lake sturgeon, *Acipenser fulvescens*, Knights, Vallazza, Ziegler & Dewey (2002) noted these fish appeared to be blocked by gated dams when they were in controlled river condition (i.e. not in open river). A similar scenario was noted for the paddlefish (*Polyodon spathula*) by Zigler, Dewey, Knights, Runstrom, & Stingraeber (2004) who noted that most LD passages of this species seemed to occur at times when their gates were likely out of the water. In another seminal study of both up- and down-stream passages of 11 species of fish across 5 LDs in the middle Mississippi River, Tripp et al. (2015) noted that nearly 80% of all upstream passages occurred during times of open river. In addition, they detected that some species are seemly more efficient at passing than others, suggesting possible differences in fish behavior or physiological swimming ability. In addition, Tripp et al. (2014) described a relationship between gate opening and passage rate, although they unfortunately lacked data on water velocity. Finally, in the only study to specifically and systematically monitor passages through a lock versus spillway gates, Lubejko et al. (2017) found that only a few (3) of several hundred acoustically-tagged Silver and Bigheaded Carp were able to overcome spillway gates in controlled river condition at Starved Rock Lock and Dam in the Illinois River. These authors specifically speculated that the low passage rates for Bigheaded Carp at this location were related to high (but unknown) water velocities under partially closed spillway gates.

Seeking to quantify and test the relationship between spillway gate operation, water velocity, and fish swimming abilities at LDs, we (Zielinski, Voller & Sorensen, 2018) recently developed an agent-based fish passage model (FPM). Our FPM models high resolution water velocity data using computational fluid dynamics (CFD) models of different operating conditions of spillway gates (i.e. degree to which specific sets of gates are opened according to flow). It then pairs these values with fish swimming performance data for different species of difference sizes to predict if, when, and where fish might pass. The model calculates a fish passage index (FPI) based on the percent of fish that attempt to pass and might be expected to succeed. It can consider different sets of gate operating conditions at different LDs to create precise simulations of local flow (hydraulics), but requires data on fish swimming performance. The model presently assumes that fish swim upstream following a path of least resistance until they physiologically exhaust (a likely over-estimate, but reasonable as few fish swimming behavior data are available). Although initial simulations of the FPM seemed reasonable, a direct test of this possibility has not yet been performed. This FPM offers an opportunity to both explain and predict passage rates for different species of fish at different locations, and perhaps modify these passage rates to block invasive fish by altering gate operation without causing scour.

The present study determined the upstream passage rates of several species of fish through a lock and dam in the Upper Mississippi River to quantify the rates with which these fishes passed, describe the path they use (i.e. lock or spillway gates), and how these rates are borne out by our FPM. With one exception (Walleye), the passage of the fish we studied had not been studied before.

3.2.3 METHODS

3.2.3.1 Study Location

Our study took place in the Upper Mississippi River at Lock and Dam 2 (LD2), Hastings, Minnesota, USA (44°45’35” N 92°52’09” W). This structure was chosen because it is relatively typical of others, its fish populations are relatively typical of the Upper Mississippi River and it is located close to us making it practical. This LD is 220m long and has 19, 9-m long, tainter gates, a hydropower plant (impassable to fish because of its turbines), and an active lock chamber (39 m wide x 184m long; Figure 1). Its spillway gates are typically out of the water only 2% of the year (Fishpro, 2004). This LD lacks overflow spillways so fish can only pass through the spillway gates or lock (Figure 1).

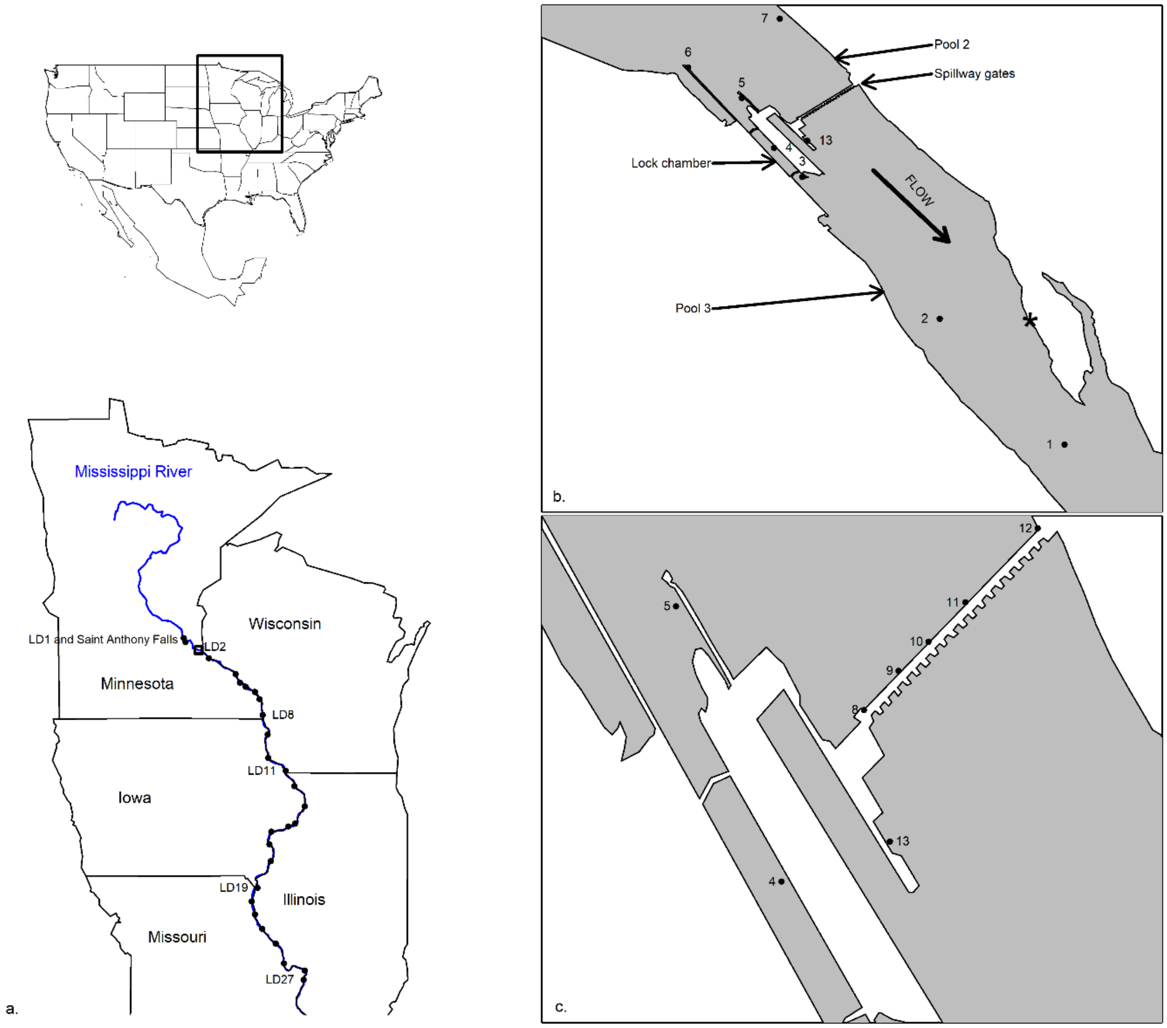

FIGURE 1 a) Location of Lock and Dam 2 (LD2) on the Mississippi River, Hastings, Minnesota, USA. b) Position of acoustic receivers on and around LD2 (* indicates the location of surgeries and tagged fish release). C) Enlargement of LD2 showing the position of spillway gate receivers (#8 - #12).

3.2.3.2 Experimental Design

To address our objective we sought to catch, tag, and track a variety of fish over 3 field seasons. We focused on the most common large fish (i.e. larger fish are most likely to pass) found in the area: Common Carp (*Cyprinus carpio*), Walleye (*Sander vitreus*), Channel Catfish (*Ictalurus punctatus*), and Bigmouth Buffalo (*Ictiobus cyprinellus*). We focused on the Common Carp because it was especially abundant through the field season, invasive, and we were able to identify swimming performance data (see below). We sought to track at least 20 individuals of each species using two strategies to increase sample size and focused on upstream movement. First, we captured, tagged, and then released fish in Pool 3 (Pool 3 fish) downstream of LD2 in the spring and late fall to capture possible spring movement. Second, we also captured fish in Pool 2 (Pool 2 fish), upstream of LD2 and then displaced them to Pool 3, hoping that they would attempt to return to their home ranges. Fish were displaced throughout the entire study. Experiments started in the fall of 2016 and continued until fall 2018, excluding the time when the river was covered with ice and LD2 was closed to boat traffic. All fish were tagged with acoustic transmitters (Section 3.2.3.3) and their passage rates assessed using an archival array (Section 3.2.3.5). Fish passage rates were also simulated using our FPM model (Section 3.2.3.7).

3.2.3.3 Fish Capture and Tagging

Fish were captured using a combination of techniques including boat electrofishing (5-12 A, 80-150 V, 20-60 % duty cycle, 60-120-pulse frequency), standard gillnets (20 min set, 90m length x 2m depth, mesh sizes (7.6, 8.9, 10.2 and 12.7cm square measure mesh), hoop nets (1.2m diameter frame, 3.8cm square measure mesh), and angling in both pools. Techniques varied with river stage, temperature, and species. Only fish larger than 50cm (TL) were kept. To reduce stress, gillnets and hoop nets were not used when water temperature was above 24^{o}C. When water temperatures were >24^{o}C only Common Carp (electrofishing) and Channel Catfish (angling) were sampled.. Captured fish were transported for tag-implantation to the surgery site located 200 m downstream of LD2 in Pool 2 (Figure 1) in a 400 L holding tank with recirculating water. Fish were anesthetized in a 1:7000 solution of eugenol (Sigma, St. Louis, MI) following established procedures (Hajek, Klyszejko, & Dziaman, 2006). A 5 cm incision was made on the ventral side of the anaesthetized fish just posterior of its pelvic fins and a tag inserted into their body cavity following established protocols (Penne & Pierce, 2008). We used 22.7g and 26.15g DART tags (model DART10, ATS, Isanti, MN, USA) which have both individually coded acoustic (3-sec pulse rate, 416.7 KHz) and radio signals (49 and 50 kHz) with an 8-12 month battery life. Once a tag had been inserted, a sterile 14-gauge needle was inserted posterior to the incision, enabling us to thread the radio antenna through the muscle wall of the fish. The incision was closed using 4 to 5 interrupted re-absorbable sutures (2-0, Ethicon PDS II). Tagged fish were then placed in the river in a 1.3 x 1.3m net pen until they recovered (approximately 20 min) before being released.

3.2.3.4 Fish Release

We released the three fish commonly caught in Pool 3 on site (Common Carp, Channel Catfish, Walleye; Table 1) and the three most common fishes caught in Pool 2 (Common Carp, Channel Catfish, Bigmouth Buffalo; Table 2) into Pool 3. There were no known mortalities and 88% of tagged fish were eventually detected by receivers upstream of the surgery site, suggesting mortality was low. Protocols were approved by the University of Minnesota Institutional Animal Care and Use Committee (#1605-33753A).

TABLE 1 Fish captured and released in Pool 3 (Pool 3 fish)

Capture periods	Species	Number	Average total length (mm)	Standard deviation (mm)	Capture dates
Spring 2017	Common Carp	15	713	34	04/20/2017 to 05/04/2017
	Walleye	13	689	39	04/19/2017 to 05/05/2017
	Channel Catfish	2	602	45	04/21/2017 to 05/05/2017
Fall 2017	Common Carp	20	721	50	10/10/2017 to 10/19/2017
	Walleye	6	663	35	10/12/2017 to 10/23/2017
	Channel Catfish	1	570	-	10/23/2017
Spring 2018	Common Carp	21	738	64	04/27/2018 to 05/10/2018
	Walleye	3	688	61	05/16/2018 to 05/23/2018
	Channel Catfish	12	755	77	04/27/2018 to 05/17/2018

mm: millimeters

TABLE 2 Fish captured in Pool 2 and displaced to Pool 3 (Pool 2 fish).

Year	Species	Number	Average total length (mm)	Standard deviation (mm)	Capture dates
2016	Common Carp	17	631	36	08/23/2016 to 09/27/2016
	Channel Catfish	5	672	33	09/27/2016 to 10/06/2016
	Bigmouth Buffalo	7	610	42	09/15/2016 to 09/27/2016
2017	Common Carp	39	684	53	05/08/2017 to 10/09/2017
	Channel Catfish	11	639	49	05/09/2017 to 06/29/2017
	Bigmouth Buffalo	14	622	48	05/22/2017 to 08/23/2017

mm: millimeters

3.2.3.5 Acoustic Array and Monitoring

Fish distribution and movements around LD2 were monitored between August-November 2016, April- November 2017, and April- August 2018 using an array of archival receivers (SR 3001-continous scan; Advanced Telemetry Systems, Isanti, MN). We used 12 receivers in 2016, and 13 in 2017 and 2018 (receiver #13 was added to monitor below spillway gates, Figure 1). Five receivers were installed in spillway gates using custom-built mounts in stop-log recesses located upstream of the gates to try and detect fish passing through the gates. Range tests showed these receivers detected fish within 250 m at times of moderate-low turbulence, with reduced and highly variable ranges at times of high flow and turbulence (especially in the spillway gates). Three receivers were also positioned in or around the lock (attached to recessed ladder rungs), two others were fixed to U.S. Coast Guard (USCG) buoys on custom ½” round bar mounts, and two were mounted to sunken concrete blocks that were attached to the shore of the river via cable. Range tests showed that the full width of the river was covered by receivers #6 and #7 (Figure 1). Receivers #1 and #2 were positioned further downstream to monitor possible mortality or downstream swimming in case fish were not encountered approaching LD2 (which they were).

3.2.3.6. Analysis of Tagged Fish Data

Data were downloaded and then filtered to remove uncertain detections (i.e. single detections that were not followed by another within 3-sec or multiples thereof up to 18-sec). We then determined the number of times that fish approached LD2 by calculating the total days that individual fish were detected immediately below it, at either receiver #3 and/or #13. An individual detection on a single day was defined as an “approach.” Approach rates between Pool 3 fish and Pool 2 fish were compared by a Mann Whitney U test. Passage rates and paths of individuals through the spillway gates or lock chamber were also examined. First, we confirmed passage through the structure to get a passage rate. A fish was considered to have “passed” when it was detected at either upstream receiver #6 and/or #7. The passage rate was the number of fish that were determined to have passed divided by the number of that species that had been released below LD2. Next, we determined path of passage. Successful passage through the lock required that a fish be detected at receivers #3, #4 and/or #5 followed by #6 or #7 in that order (Figure 2). Alternatively, to be considered as having passed through the spillway gates, passage had to include #6 and/or #7 (and possibly receiver #13) but not lock receivers #3 and #4. For a three-week period in 2018 (May 1 - May 24) receivers #4 and #5 failed; when a fish was detected at #3 before being detected upstream at #6 of #7 during this period, its passage was labelled as “unknown.” Receiver #7 failed for 97 days; to confirm that we did not miss possible spillway passages during this time, we compared passage rates when it was working (the vast majority of the study) with when it was not, and found there was no indication of missed passages (see Discussion). Because the vast majority of fish moved upstream and approached LD2 for weeks (see Results), we did not specifically evaluate downstream passage although a few were coincidentally noted. To test if passage distribution (i.e. passage rates through the lock vs. spillway gates) differed between Pool 2 fish and Pool 3 fish, we performed a 2x2 Chi-Square analysis (unknown passages were not including in this analyses) and when no difference was found (see results), we combined these fish to take advantage of the larger sample sizes. Total passage rates of Common Carp and Channel Catfish were also compared with a 2x2 Chi-Square test.

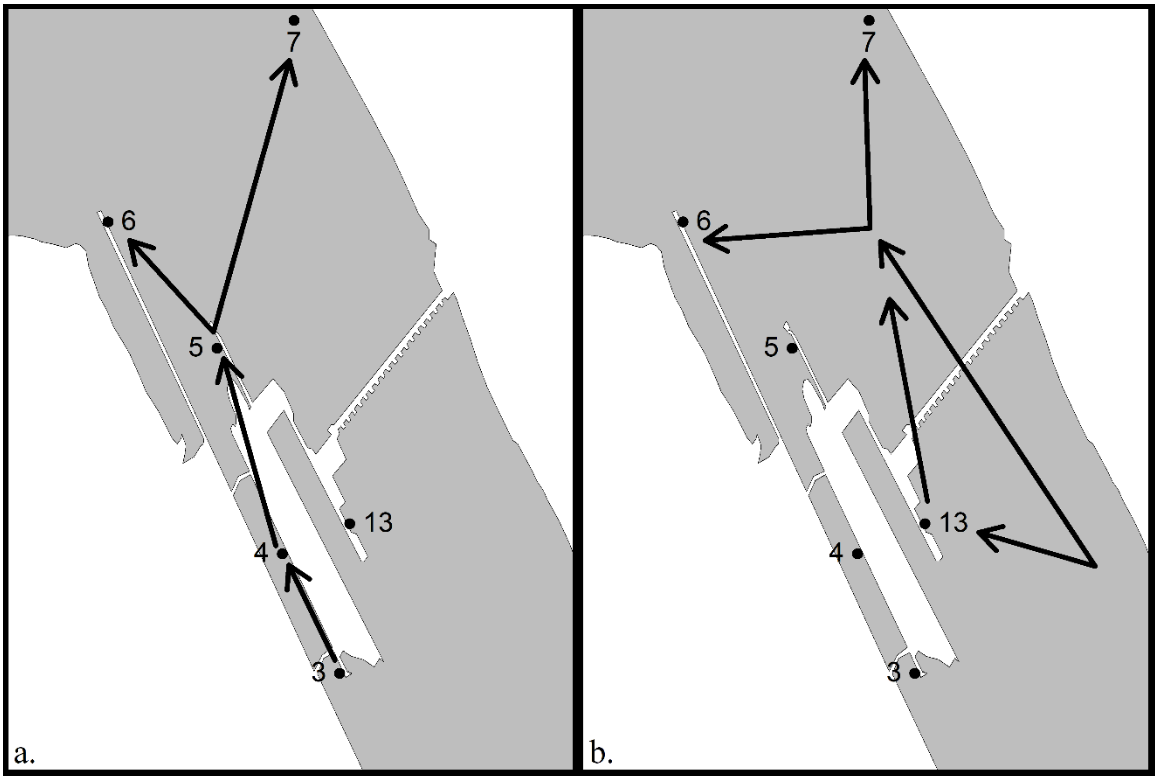

FIGURE 2 Sequence of fish detection at different locations used to determine whether fish passed through the lock chamber (a) or spillway gates (b) at Lock and Dam 2. Each number represents the location of a receiver. Arrows indicate the sequence of detections.

3.2.3.7 Computational Agent-Based Fish Passage Model (FPM)

Hypothetical passage rates of Common Carp through LD2 was modeled using our FPM model (Zielinski et al., 2018). This took place in two steps. First, we modeled the hydraulic conditions of the river throughout the study (8 river flows between 7,000 cubic feet per sec (cfs) and 61,000 cfs (open river). We simulated flow distribution and water velocities below LD2 using ANSYS Fluent (version 19.2) computational fluid dynamics (CFD; see Supporting Information I). The model (which had been validated at LD8) was developed using detailed river bathymetry, lock and dam structure engineering plans, gate operations, and river flows (discharge) provided by the U.S. Army Corps of Engineers (USACE) and velocities were calculated in three dimensions. Second, we modelled

Common Carp passage through the spillway gates of LD2 using the hydraulic data previously calculated for all 8 river flow conditions. We only examined Common Carp because we had the most telemetry data for this species and Common Carp were the only species with data on the swimming performance for large individuals (> 50cm TL), which reflects the size of fish that we were tracking. Because data for Common Carp were sparse and had not been fit to a swim speed to endurance time curve before, we derived a relationship for its swimming performance using available data (see Supporting Information II). We then used established protocols for the FPM (Zielinski et al., 2018) to generate 5000 "agents" (simulated Common Carp) which were assigned sizes and swimming abilities that matched the range of the fish we had captured (i.e. six 5 cm size classes from 60 to 80 cm). Agents were then randomly seeded 200 m downstream of the LD at a depth of 1 m (studies using Common Carp implanted with depth acoustic tags showed them to swim at a medium depth of 1.1 m ± 1 m; Section 3.3.5.3) and their upstream swimming and passage simulated. Simulations were repeated for all 8 flow conditions and fish sizes with the option of lock passage removed. A passage index (FPI) was then calculated by dividing the total number of successful passages by the total number of individuals simulated in each size class, and these values binned into 10 groups (500 agents in each group) to obtain a sample variance. Mean ± S.D. passage index values were then calculated and plotted for each flow and compared to that seen for tagged Common Carp.

3.2.4 RESULTS

3.2.4.1 River Conditions

During the course of this study, the Mississippi River fluctuated between 7100 cfs and 67000 cfs and had a median river discharge of 32160 cfs (1st quartile: 22480 cfs, 3rd quartile: 42880 cfs). LD2 was in open river condition a total of 5 days (30th of April to 4th of May 2018, Figure 3, Figure 4a).

3.2.4.2 Approach Behavior

We detected a grand total of 164 (88%) of our tagged fish below LD2 (i.e. 93% of tagged Common Carp, 86% of Walleye, 87% of Channel Catfish, and 67% of Bigmouth Buffalo) on at least one occasion. Pool 3 fish approached the downstream side of LD2 numerous times; Common Carp approached a median of 28 times (16.3, 43.5 first and third quartiles), Channel Catfish 5 times (3.0, 11.5), and Walleye 29 times (12.5, 47.0). Similar values were noted for Pool 2 fish: Common Carp approached a median of 14 times (5.0, 48.0), Channel Catfish 5 times (3.0, 14.3), and Bigmouth Buffalo 6 times (3, 7.8). No differences were noted in the approach behavior of Pool 3 and Pool 2 Common Carp or Channel Catfish (Mann Whitney U test: $W=1084.5$, $p = 0.084$; Mann Whitney U test: $W=85.5$, $p > 0.1$).

3.2.4.3 Passage Rates and Paths

A grand total of 186 fish were captured, tagged, and released below LD2, of which 54 (29%) eventually passed through it (Table 3), with most fish passing through the lock chamber, but some did pass though the spillway gates (mostly during open river condition).

Only 8 (4%) of these fish could not have their passage route determined. Known passages through the lock (N=36) occurred at all river stages (Figure 4c) while all 10 known spillway gate passages (with the possible exception of one) occurred during open river (see below). Known passages through the spillways gates were rarely confirmed by receivers located in the spillways (receivers #8 - #12), but these events (as monitored by upstream receivers #6 and #7) coincided with open river, when turbulence was extremely high in the spillways, which drastically reduced receiver range.

Of a total of 93 Pool 3 fish, 24% passed through LD2 (Table 3). Of 56 Common Carp, 21% passed through LD2 of which 7% passed through the lock chamber (Figures 3, 4c) and 5% passed through the gates (9% unknown; Figures 3, 4d; Table 3). All 3 Common Carp known to pass through the gates did so in 2018 during open river conditions when river flow exceeded 61,000 cfs (Figure 3). Of the 22 Pool 3 Walleye, only 14% passed, and all went through the lock (Table 3). Of the 15 Channel Catfish caught and released below LD2, 47% passed through LD2 with 20% passing through the lock chamber and 7% passing through the gates in 2018 during open river (20% unknown; Table 3).

Out of the 93 Pool 2 fish, 34% passed through LD2 (Table 3). Of 56 Common Carp, 30% passed through LD2, with 23% passing through the lock, and 7% passing through the gates (Figure 4b,c). All spillway gate passages occurred in 2018 when the river was in open river condition, except for one that occurred the following day when the river was still at 60200 cfs (Figure 3). There were no unknown passages. Of the 16 Pool 2 Channel Catfish, 63% passed through LD2, all through the lock (Table 3). There were no unknown passages. Of the 21 Pool 2 Bigmouth Buffalo, 24% passed through LD2, 14% of which passed through the lock, and 12% passed through the spillway gates in 2018 during open river. There were no unknown passages.

Pool 2 Common Carp used the lock more frequently than did Pool 3 Common Carp (23% and 7% respectively) as did Channel Catfish (63% and 20%; Table 3). However, the passage routes of Pool 2 and Pool 3 fish were not different (Common Carp: Chi-Square=0.21, df=1, p= 0.65; Channel Catfish: Chi-Square=0.24, df=1, p= 0.60). Accordingly, we combined these datasets for Common Carp to plot overall passage rates for this species through the lock and spillways gates at different flows that matched those used for the FPM to evaluate the possible relationship (Figure 4b, c). When Pool 2 and Pool 3 fish were combined, we detected a species difference in the proportion of upstream passage rates for Common Carp and Channel Catfish (26% and 55%, respectively; Chi-Squared=8.04, df=1, p <0.01).

TABLE 3 Upstream passage rates through the lock and spillway gates at Lock and Dam 2.

Species	Experiment	Fish captured	Lock	Spillway	Unknown	Total
Common Carp	Pool 3	56	4	3	5	12 (21%)
	Pool 2	56	13	4	0	17 (30%)
	Total	112	17 (15%)	7 (6%)	5 (4%)	29 (26%)
Channel Catfish	Pool 3	15	3	1	3	7 (47%)
	Pool 2	16	10	0	0	10 (63%)
	Total	31	13 (42%)	1 (3%)	3 (10%)	17 (55%)
Walleye	Pool 3	22	3 (14%)	0	0	3 (14%)
Bigmouth Buffalo	Pool 2	21	3 (14%)	2 (10%)	0	5 (24%)
Grand Total		186	36 (19%)	10 (5%)	8 (4%)	54 (29%)

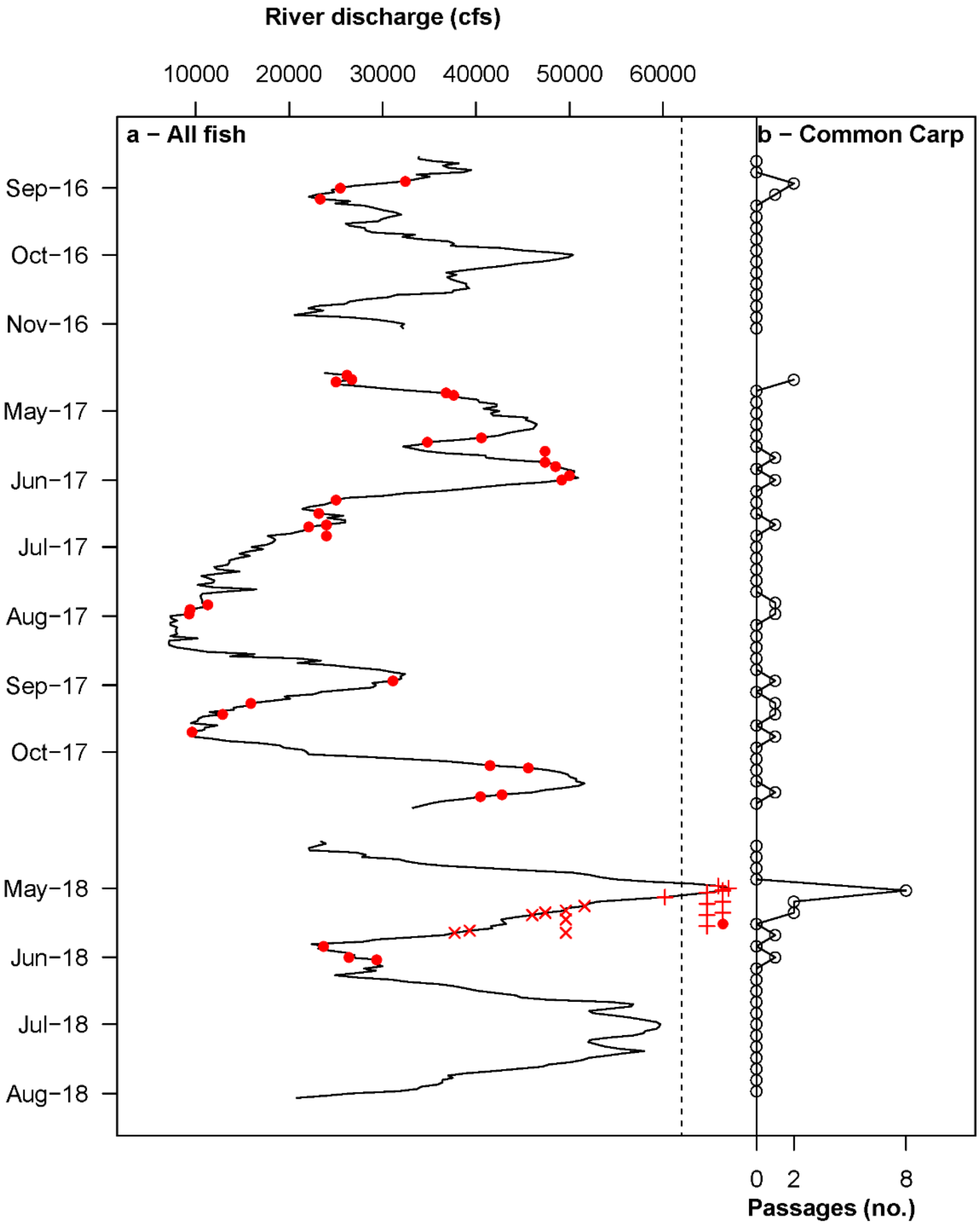

FIGURE 3 Plot showing fish passages monitored throughout this study. The right graph (b) shows the number of total passages for Common Carp only. The left graph (a) shows all passages for all fish versus river discharge. Each symbol represents an upstream passage (circle: lock chamber, +: spillway gates, x: unknown). The dashed line denotes when the river went into “open river” and the gates came out of the water.

3.2.4.4 Fish Passage Model

Hydraulic modelling showed that while velocities at a depth of 1 m below LD2 did not vary greatly (except for homogenization) with river flow for flows below 61000 cfs (open river), very notable differences were seen when the gates were opened (Figure 5). In addition, when we examined water velocity with depth, we found that velocities greater than 3 m/sec occurred directly below the gate openings except during open river when velocities dropped below 2 m/sec throughout the water column (Figures 6, S1.1). Similarly, the FPM for Common Carp predicted that no Common Carp could pass for all flow conditions less than 45000cfs (FPI of 0%), only a few might pass at 45000 cfs (FPI of 1%), and a relatively large number could pass during open river (>61 0000 cfs; FPI of almost 30%; Figure 4d). Models of fish tracks suggested Common Carp of the size we tracked might pass at many locations across LD2 during open river but are blocked across the structure at lower flows (Figure 5a, b).

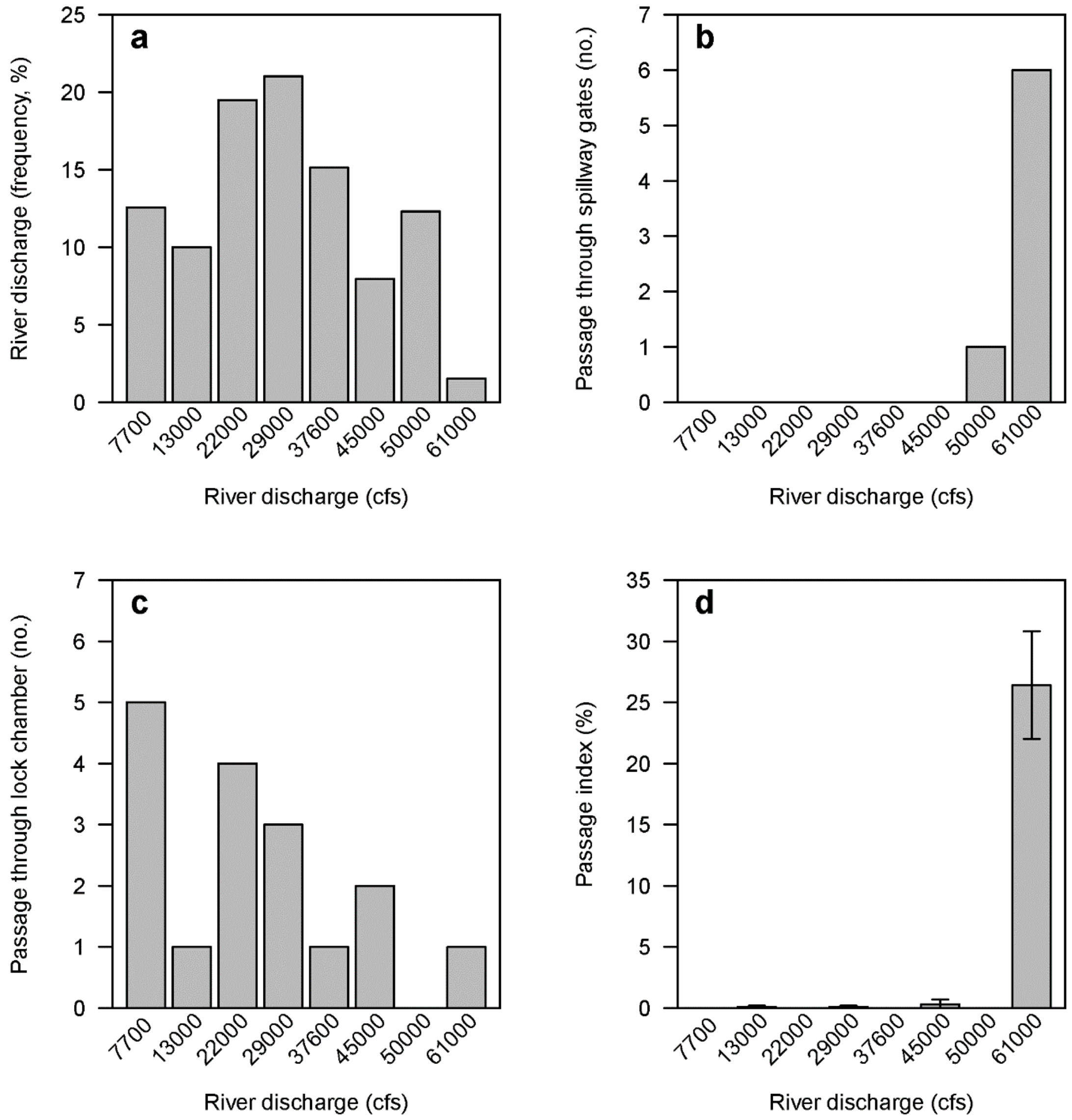

FIGURE 4 Common Carp passage rates and river conditions. a) Relative frequency of river flows experienced during the course of this study. b) the number of Common Carp passages through the spillway gates during different river flows. c) the number of Common Carp passages through the lock chamber during different river flows. d) Passage index through the spillway gates for Common Carp as calculated by the FPM. 61000 cfs is open river condition.

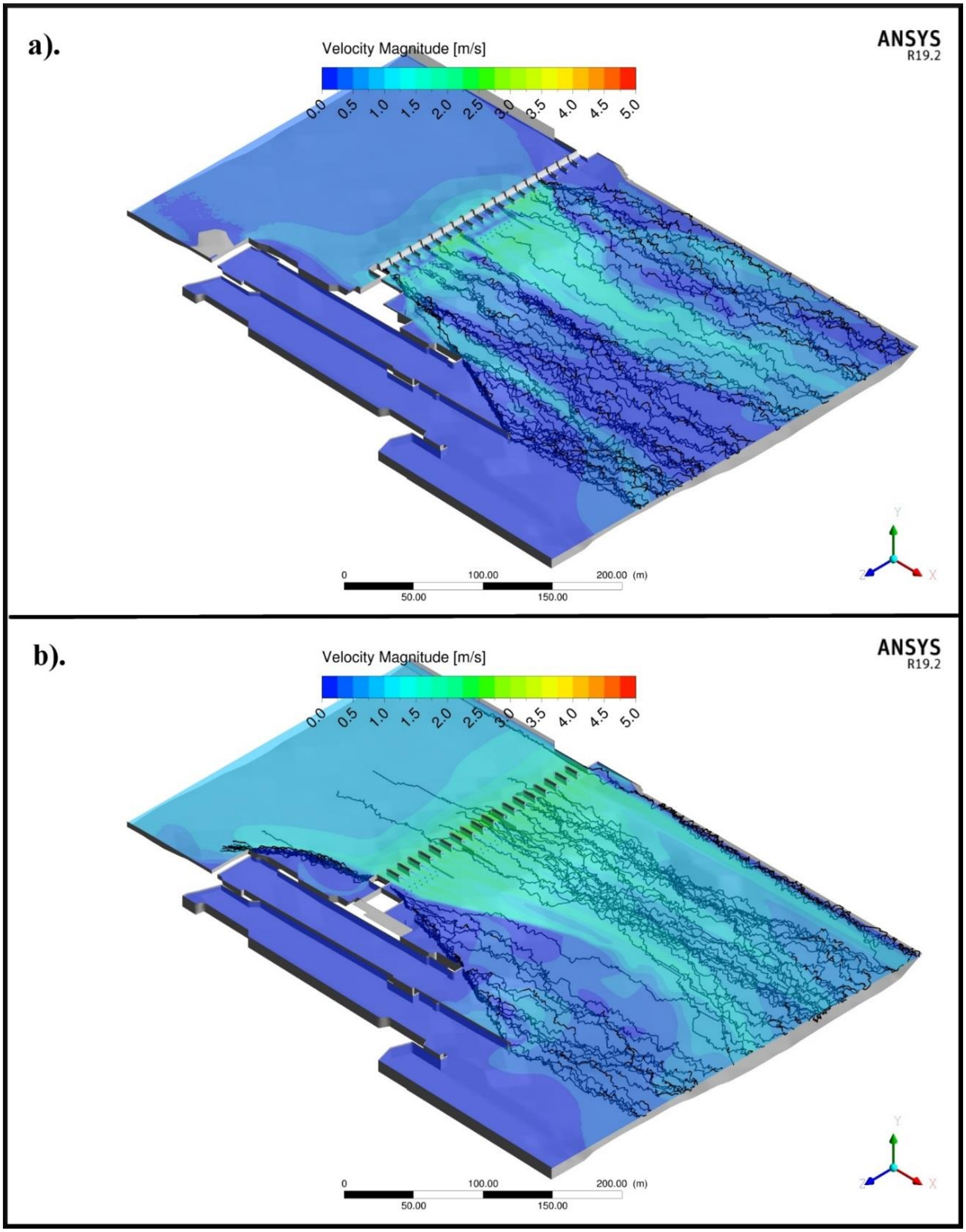

FIGURE 5 Plot showing simulated Common Carp (black tracks) surperimposed on calculated surface water velocities downstream of LD2 at: a) 29000cfs and b) 61000 cfs (open river).

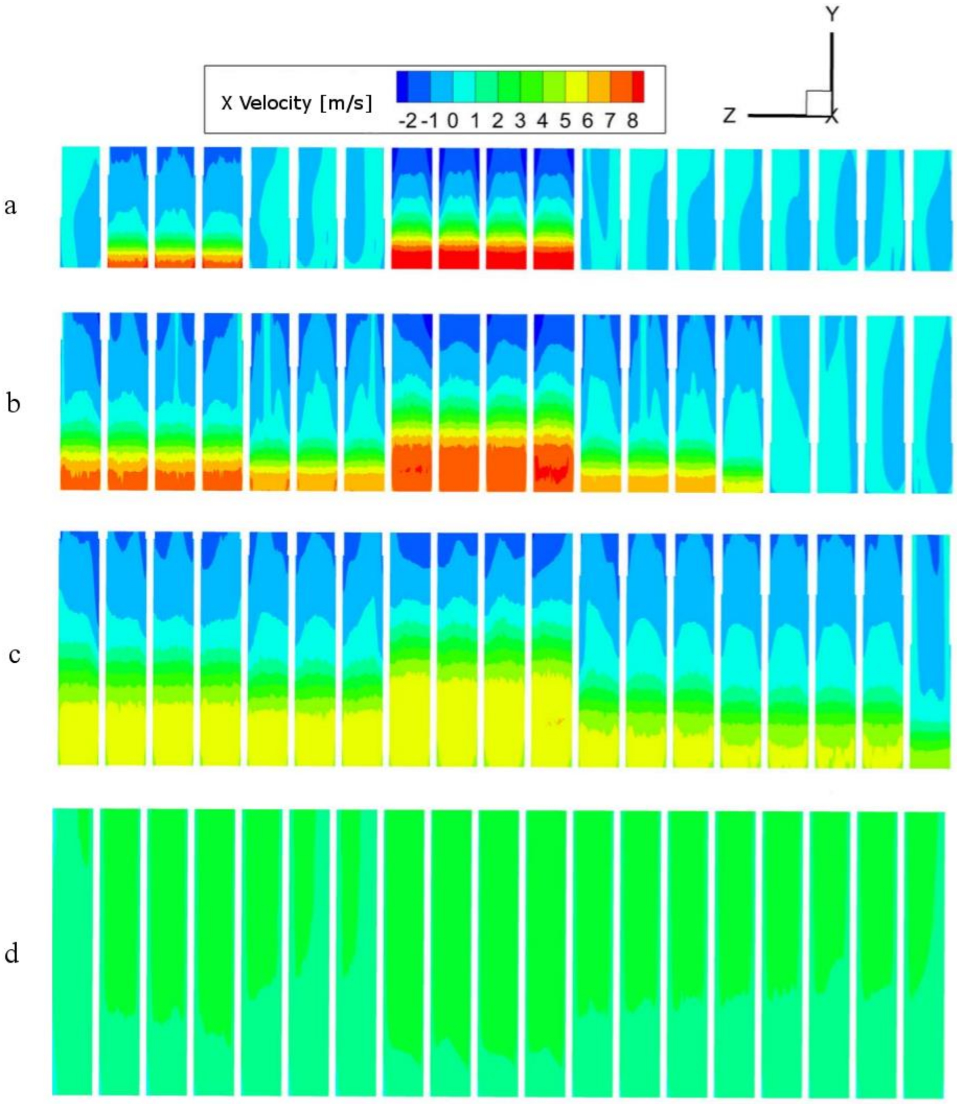

FIGURE 6 Plot showing calculated water velocities (meter/second) with depth running across the width of LD2 from the west to the east side of the spillway gates at: a) 13000cfs; b) 29000 cfs, c) 45000 cfs; and d) 61000 cfs. Dark blue colors are ares of low water flow because they are blocked by gates.

3.2.5 DISCUSSION

This study investigated upstream passage of Common Carp, Channel Catfish, Walleye, and Bigmouth Buffalo through a Mississippi River lock and dam whose spillway gates rarely opened fully. We found that outside of a short 5-day period which coincided with open river conditions and low water velocities under the spillway gates, these species of fish did not pass through the spillway gates, although they did pass through the lock chamber at a modest-and species-specific rate. It appeared that the lack of passage through the spillway gates was caused by high water velocities that exceeded their swimming performance as also described by our FPM. The high passage rate during open river is consistent with that suggested by other studies (Lubejko et al., 2017; Tripp et al. 2014). Together, our results suggest that many LDs likely impede upstream migration of both native and invasive fishes because their water velocities as predicted by a FPM.

The most important finding of this paper is likely that the water velocities created by spillway gates and calculated by a FPM exerted quantifiable effects on fish passage through LD2. This model accurately predicted that even large Common Carp (80 cm) could not pass through LD2 gates except when the gates were completely (or very nearly) open. Although we experienced receiver failure on several occasions and may have missed some passages when receivers #4 and #5 failed (19 days of 379 days in the study), it seems very unlikely that we missed any through the spillway gates, even when receiver #7 failed (97 days all during closed river), because it did not detect any spillway passages during the entire 282 day period that it was working and this included the entire spectrum of river flow conditions including the 5 days of open river (when all spillway gate passages were also noted [by it]). Additionally, the failure of fish to pass during controlled river was highly consistent with both the water velocities we calculated and model predictions. Nevertheless, our study represents but a single test of the FPM at a location which is relatively impermeable to passage (LD2 gates rarely out of the water), and additional tests of the FPM are warranted at more permeable locations. Notably, this study also highlighted the need to collect more data on fish swimming behavior and performance to update the model. In the meantime, it seems reasonable that our FPM (given its conservative nature) might be used to guide efforts to adjust gate openings to impede Bigheaded Carps in the Upper Mississippi River (Zielinski et al., 2018).

We believe our second most important finding is that different species of fish used the lock chamber in different species-specific manners that are seemingly not velocity dependent. Our data on Common Carp, Channel Catfish, and Bigmouth Buffalo are the first of their kind. Differences in passage rates were mirrored in differences in approach behavior (timing and frequency), suggesting the differences relate to behavior and not solely swimming performance (and size) of fish. We found that lock chamber passages represented 67% of all passages for all species, with 81% being for Pool 2 fish, and 45% for Pool 3 fish. Our passage rate for Pool 3 fish exceeded that noted by Tripp et al. (2014) and Lubejko et al. (2017) but with the exception of Walleye, we studied different fish species, strongly suggesting there are species-specific differences in behavioral preferences as previously suggested (Tripp et al., 2014). Remarkably, we noted particularly high passage rates (60%) for Pool 2 Channel Catfish and 45% for Pool 3 Channel Catfish. These rates exceed previous values reported for Bigheaded Carp (Tripp et al., 2014; Lubejko et al., 2017), perhaps a good omen for carp control, as they might be easier to stop. Interestingly, lock passage rates were seemingly not influenced by river flow, even for

Common Carp, suggesting lock passage was not necessarily driven by failure to pass through the gates but rather a behavioral preference. It will be important to develop a better understanding of lock passage behavior if sensory deterrents are to be added to these structures to either block invasive fish (Taylor et al., 2005; Vetter et al., 2017; Zielinski & Sorensen, 2016) or gate openings altered to facilitate native fish passage (Moser, Darazsdi, & Hall, 2000; Smith & Hightower, 2012).

Finally, our data strongly suggest that riverine Common Carp and Channel Catfish displayed homing behaviors (when displaced from Pool 2), and this attribute could be used as a tool to study fish passage at other LDs. Although homing has previously been documented in Common Carp (Crook, 2004; Dauphinais, Miller, Swanson, & Sorenson, 2018) and Channel Catfish (Pellett, Van Dyck, & Adams, 1998), our demonstration is the first in a large river and the clearest through its systematic displacement of fish year-around. Although we did not measure a statistical difference between the behavior (approaches or passages) of displaced Pool 2 fish and Pool 3 fish, it appeared that Pool 2 fish exhibited slightly stronger movement upstream and more passed through the lock chamber. Additionally, the fact that both Pool 2 fish and Pool 3 fish passed LD2 with relatively high and similar number of times, and were associated with many approaches for many weeks, suggesting that their behaviors reflected a drive to move upstream (and not simply milling in the area). Nevertheless, it is important to note that fish were displaced at various times throughout the field season and their passage rates might have been influenced by possible differences in natural migratory behavior. Further work is needed on natural movement and habitat usage of riverine fishes to better understand the impact of LDs.

In conclusion, our study is the first to look at fish passage through a lock and dam structure in the Upper Mississippi River that simultaneously models water velocity and fish passage. This study shows in a quantifiable manner that water velocity likely determines passage through spillway gates. It strongly supports the long-suspected significance of spillway gate operations (both closed and open river) to fish passage and the supposition that LDs which rarely experience open river conditions are especially important to riverine fish population dynamics and blocking invasive fish. Notably, we also show how species-specific behavioral tendencies of four previously unstudied species pass through lock chambers. Spillway gate and lock passage could be used to managing invasive carp, perhaps in combination with our FPM which could be further improved, now that we know more about how fish pass. Lastly, we demonstrate how little is understood about river fish in general and the need for more studies of their physiology and behavior, especially with the arrival of invasive species.

3.2.6 ACKNOWLEDMENTS

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3.2.8 Supporting information I: Simulating the flows and water velocities that fish encountered below LD2 (Submitted with the above draft manuscript to River Research and Applications.)

Following Zielinski, Voller, & Sorensen (2018), a three-dimensional unstructured tetrahedral mesh of the Mississippi River surrounding Lock and Dam 2 (extending ~300 m up- and –downstream) was generated first using the ANSYS meshing software using detailed construction drawings and sub-meter river soundings from the U.S. Army Corps of Engineers (USACE). Upstream boundary conditions were specified as a uniform depth averaged velocity. Water surface boundary conditions were treated as a rigid lid (i.e., zero shear stress) set to match the longitudinal water surface profile obtained from gauge records. The flow field was then simulated using ANSYS Fluent software that uses a finite volume method to solve the Reynolds-averaged Navier-Stokes (RANS) equations and k-ε turbulence model with wall functions. The velocity fields were validated using ADCP survey's ~100 m downstream of the dam at 29,000 cfs and 94,325 cfs (the latter condition was not used in the fish passage analyses). The 3D computational meshes used in the CFD model had approximately 1.2-2.1 million nodes. Unsteady RANS modeling was also performed to appropriately model complex flow at high Reynolds numbers and obtain the mean velocity and distribution of turbulent fluctuations at all nodes in the computational mesh. Velocity distributions downstream of the spillway gates is highly influenced by the height of gate opening. An example cross section of our velocity calculations is shown in Figure S1.1.

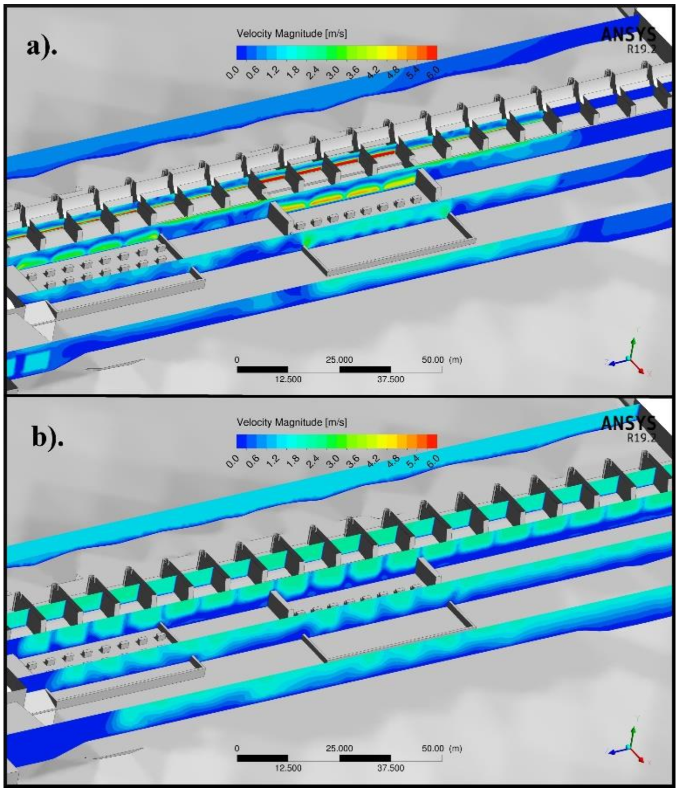

Figure S1.1 Velocity magnitude contours at cross-sections 20 m upstream and 5 m, 15 m, 25 m, and 45 m downstream of the spillway gates at river discharges of (a) 29,000 cfs and (b) 61,000 cfs (open river). Note the high velocities near the river bottom during 29,000 cfs and the near uniform and reduced velocities during 61,000 cfs.

3.2.9 Supporting information II: Estimating Common Carp swimming performance

The FPM identifies how specific gate openings can generate particular water velocities that may cause fish to exhaust their physiological swimming abilities, thereby prohibiting passage. The model requires a numeric understanding of the swimming performance (i.e. the ability of fish to swim specific speeds for specific lengths of time) of species of interest and for appropriate fish lengths. The present study was interested in large fish (> 50 cm) and while no such data existed for Walleye, Bigmouth Buffalo or Channel Catfish, several partial flume swimming tests had been conducted for large Common Carp (Furniss et al. 2006 and data and references therein) as well as the related bigheaded carps (Hoover, Zielinski & Sorensen, 2016), allowing us to create a reasonable facsimile.

As a first step we plotted and then fit all published unsustained swim speed data (<100 min duration) for Common Carp, Bigheaded Carp and Silver Carp at all fish lengths. The resulting regressions were similar for both Bigheaded Carps and also paralleled that of the Common Carp (Figure S2.1), suggesting that we could reasonably calculate swimming performance as we had previously for Bigheaded Carps (i.e. no mode between prolonged and burst swimming; Hoover et al., 2017). Additionally, we observed that like the Bigheaded Carp, the Common Carp swimming speeds plateaued for fish above 50 cm, again suggesting that, as for Bigheaded Carps, swimming speed is not highly dependent on total length (TL) after this point and we could assume a relationship of swim speed (normalized by total length) to endurance time for all Common Carp above 50 cm TL. Accordingly, we applied the large Common Carp swimming performance dataset to calculate the parameters (a, b) needed for the FPM Model (Table S2.1; Figure S2.2) by fitting a curve on the data provided by Furniss et al. (2006). The standard deviation of the swimming performance curve coefficients was conservatively set to one to consider a greater range of possible swimming performance.

TABLE S2.1 Size range and swimming performance characteristics (a and b) of Silver and Bigheaded Carp (Hoover et al., 2017) and Common Carp (Furniss et al., 2006).

Species	**Total length (mm)**	**Maximum sustained swim speed (TL/s)**	**a (mean± sd)**	**b (mean± sd)**
Silver Carp	600-1000	1.25	1.92±0.65	-1.02±0.33
Bigheaded Carp	700-1100	1.00	5.52±0.73	-2.98±0.41
Common Carp	1180	1.00	4.36±1.00	-2.66±1.00

mm: millimeters, TL: Total length, s: second, sd: standard deviation

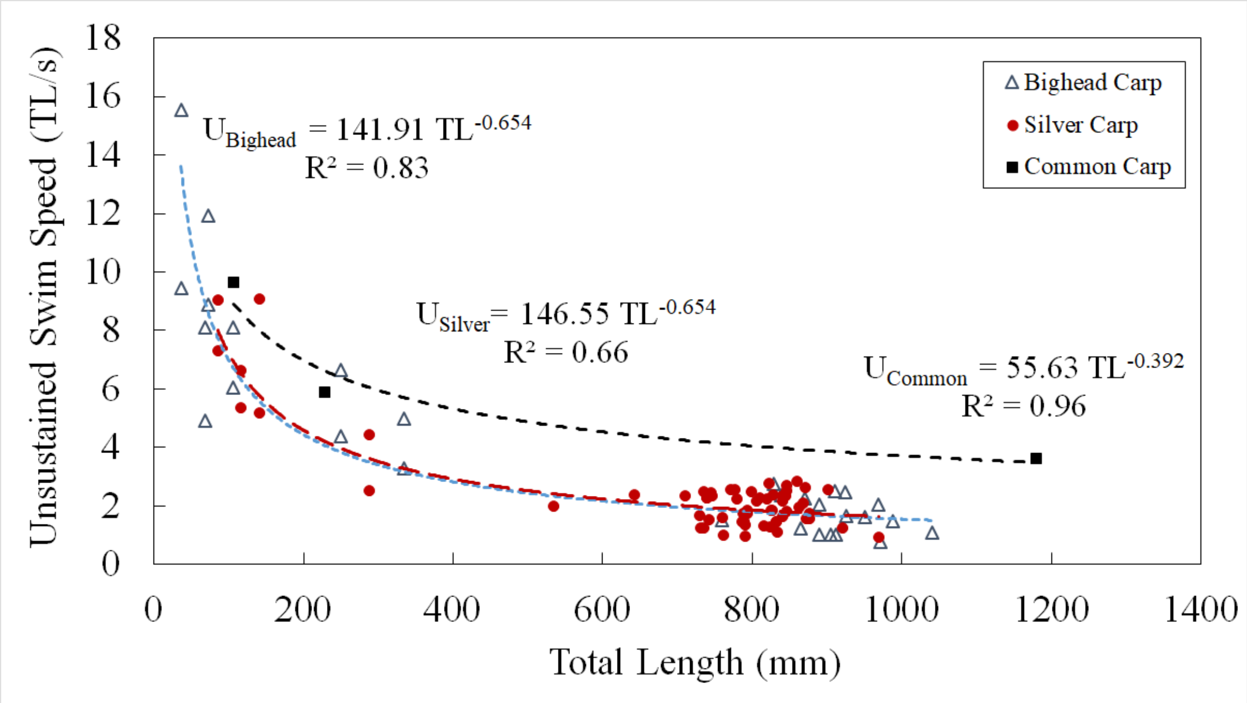

FIGURE S2.1 Comparison of prolonged and burst swim speeds (Total length per second: TL/s) relative to body length for Silver and Bigheaded Carp (Hoover et al., 2017) and Common Carp (Furniss et al., 2006; Tudorache, Viaenen, Blust, & De Boeck, 2007; Tudorache, Viaene, Blust, Vereecken, & De Boeck, 2008). Common Carp data points are mean values as raw data are not available.

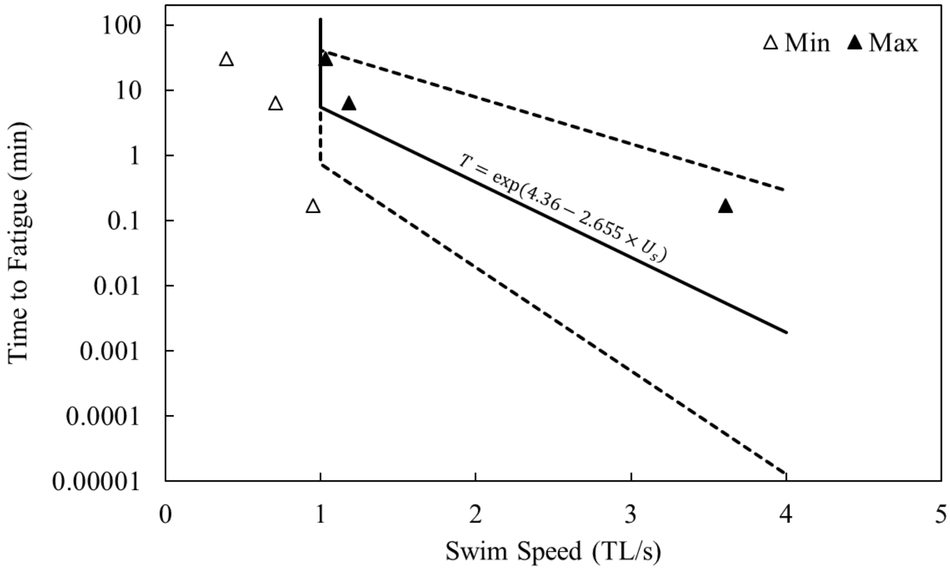

FIGURE S2.2 Common Carp swimming performance curve (mean – solid line, ± S.D. – dashed lines) used in FPM and minimum (open triangle) and maximum (solid triangle) prolonged and burst swim speeds identified for a Total length (TL) = 1180 mm Common Carp in Furniss et al. (2006). s: second.

3.2.10 REFERENCES

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3.3 DATA REPORT ON THE BEHAVIOR, DISTRIBUTION AND SWIMMING DEPTH OF ADULT COMMON CARP AND CHANNEL CATFISH DOWNSTREAM OF LOCK AND DAM 2 (a possible manuscript for publication)

3.3.1 SYNOPSIS

Radio and acoustic tracking studies of adult Common Carp and Channel Catfish were conducted downstream of Lock and Dam 2 (LD2) to provide information on the behavior of these fishes that could be used in a new fish passage model. This data compliments information collected on fish passage rates (see Section 3.2 which was conducted at the same time). To the best of our knowledge, this is the first time that information on fish swimming behavior (e.g. swimming depth, approaches, overall behavior) has been collected below a Mississippi River lock and dam. Besides being of basic interest, this information could eventually be used to guide strategies for allowing or blocking fish passages through these locks and dams, perhaps by helping create a new computational fish passage model (FPM) that includes behavioral parameters in addition to physiological ones (visa via Goodwin et al. 2014). This new model might then calculate passage rates versus a simple index and would be of special value for native fishes. As part of our study on fish passage, 84 Common Carp and 32 Channel Catfish were captured, tagged, and tracked from a boat and shore in 2016, 2017 and 2018 as they approached LD2. Although we experienced technical difficulties detecting tags in deep water (radio tags) and turbulent waters (acoustic tags) immediately below LD2, we discovered that many detections occurred along one shoreline where water velocities were relatively low, suggesting fish follow the shoreline and find low flow areas. Further, we also found that these fish then repeatedly swam upstream to the spillway gates (a behavior we termed “approaches”), suggesting they challenge it repeatedly. These fish also appeared to show depth preferences; Common Carp seemed to favor the upper 1 m of the water column, except near the spillway gates where they appeared to swim at 2-3 m. These behaviors may explain why and how these fishes were observed swimming through the spillway gates as soon as the spillways gates lifted fully at the time of open river (see section 3.2). Portions of this section (i.e. 3.3) might be used in an eventual manuscript submission.

3.3.2 INTRODUCTION

To understand whether and how fish pass through locks and dams, and thus how passage might be either enhanced (native fish) or suppressed (invasive fish), an understanding of both the physiological abilities of fish to overcome high water velocities, and their distribution and behavior is required. Recently, we developed and tested (Section 3.2) a computational fish passage model (FPM, Zielinski et al. 2018) based solely on physiological swimming performance (ability to swim against current). It shows that Common Carp are much more likely to pass Lock and Dam 2 (LD2) during low velocity conditions that occur at the time of open river stage, which occurs just a few days in most years at the location tested. However, this particular model is highly conservative and likely overestimates passage rates even in relative terms, as it is based solely on physiological capability. Further, it does not include fish behavior. In particular, it assumes (in the absence of behavioral data) that fish swim upstream following the path of least resistance (which they are assumed to be able to discern) until they either successfully pass or fail due to complete exhaustion. While this model calculates an index of possible passage rates, it does not estimate actual passage rates (just an index) – to do so would require information on the actual distribution of fish and their behaviors. This study sought to address these issues. It asked four questions: 1) What is the distribution of specific fish species relative to water velocity below Lock and Dam 2?; 2) In what manners do fish swim towards this Lock and Dam?; 3) Do fishes challenge lock and dams repeatedly and for extended periods of time?; and 4) At what depth do they swim? Our study focused on Common Carp and Channel Catfish, as they are the most common large species at our study site. This document is presented as a draft data report.

3.3.3 EXPERIMENTAL DESIGN: FISH MOVEMENT BELOW LOCK AND DAM 2

For this study, we manually radio tracked a portion of the DART-tagged fish used for the fish passage study that had been captured in either Pool 2 or Pool 3 and released in Pool 3 (N=87; Section 3.2). We also manually tracked fish equipped with acoustic transmitters (N=40). We added acoustically tagged fish to this portion of our study because we found that radio tagged fish were generally not detectable at depths greater than 4 m (see Section 3.3.4.2). While a useful addition, we also found that acoustic tags could not be detected in turbulent waters (see section 3.3.4.2). Approximately three times a week, we surveyed 8 locations downstream of LD2 in Pool 3 for fish, spending about 30min at each location surveying each spot to determine if either radio- or acoustic- tagged fish were detectable and present. We typically covered all 8 locations establishing an overall fish distribution (see section 3.3.4.3), we then tracked individual fish (see section 3.3.4.4). Individual fish were tracked if they were approaching the spillway gates or were already near them. We tracked individual fish for 1-3 h or until we could no longer detect them before tracking a different individual. While tracking, we noted depth (with acoustic tags), and position.

3.3.4 METHODS

3.3.4.1 Fish capture, tagging and detection

This study was conducted as part of the fish passage study (Section 3.2). Fish were captured in either Pool 2 or Pool 3 using a combination of boat electrofishing, gill nets, hoop nets or angling as described in section 3.2.3. Briefly, they were anesthetized, and either equipped with dual acoustic radio tags (DART10, 22.7g or 26.15g, ATS, Isanti, MN; Frequency: between 49 MHz and 50 MHz) or acoustic tags (DT-97-L, 19g, 86mm, Sonotronics, Tucson, AZ; Frequency: 70 to 83 KHz), and released into Pool 3 about 200m below LD2 (see Section 3.2.3). In addition, 40 fish were tagged with acoustic Sonotronics tags (Table 1). The surgical procedure was the same as that described in section 3.2.3.3. A total of 87 (63 radio and 24 acoustic) tagged Common Carp and 32 (16 radio and 16 acoustic) tagged Channel Catfish were tracked. Finally, a small number (N=8) of ATS depth-sensitive tags were implanted in Common Carp. These depth tags could only be read by archival ATS receivers located on the LD (see Fish Passage Study, Section 3.2), therefore, they were not used/able to actively track these fish.

Fish localization for both radio (ATS- DART) and acoustic (Sonotronic) tags was performed using bi-angulation (e.g. Bajer et al., 2010). Once a fish was detected, we recorded the GPS position of the boat and estimated the direction where the fish was relative to the boat (i.e. compass bearing) using an aerial radio antenna (radio) or an underwater hydrophone (acoustic). This step was repeated from two different locations, so the fish position could be calculated as the crossing of two bearings. Bearings were obtained from the boat or land (i.e. lock and dam structures or shore) with the radio antenna, but could only be obtained from the boat using the acoustic hydrophone.

TABLE 1 Period of capture and number of fish for each tag type used in this study.

	Pool 2 Common Carp	**Pool 3 Common Carp**	**Pool 2 Channel Catfish**
Radio tags (DART, ATS)	N= 48 From Aug 23-2016 to Sep 6-2017	N= 15 From Apr 20-2017 to May 4-2017	N= 16 From Sep 27-2016 to June 29-2017
Radio tags (DART, ATS) equipped with depth sensor	N=8* Sep 6-2017	-	-
Sonotronics acoustic tags	N= 17 From Aug 4-2017 to Sep 7-2017	N= 7 May 23-2018	N= 16 From May 31-2018 to Aug 18-2018

* 8 of the 48 ATS DART tags were equipped with a depth sensor which was monitored by archival receivers (not manual tracking)

3.3.4.2 Range-testing radio and acoustic tags to determine detection ability in different turbulence conditions near spillway gates.

Pilot tests were performed to: 1) test our accuracy in detecting the two types of tags, 2) test their performance in highly turbulent water and calm water (typical contrast observed at LD2 and likely other LDs), and 3) test the accuracy of depth readings given by the tags equipped with depth sensors. To accomplish the former, we attached tags at various known depths along an anchor line that was attached to a retrieval buoy suspended just below the water surface. This system was not visible so observers could not be biased. The tag was then located using bi-angulation and its estimated position was compared to the GPS position when deployed. We were consistently able to locate both types of tags within 25 meters of their actual location, similar to other studies (e.g. Bajer et al., 2010; Dux et al., 2011).

Next, we determined our ability to detect tags in highly variable turbulences near the spillway gates. We did this by dropping tags into flowing waters at different locations using a weighted rope attached to a retrieval buoy. Below LD2 we found that turbulence was accurately described by the water surface velocity map created by our FPM (Figure 1). At this structure, we usually had areas with both relatively calm water (surface velocity <0.05 m/sec) and highly turbulent water (surface velocity >1 m/s). Therefore, test tags were dropped into both calm and highly turbulent waters. For both conditions, we tested tags in 50 cm increments until they were no longer detectable. Radio-tags were detectable to a depth of 50 cm in turbulent water (velocity > 1 m/s) and 4 m in non-turbulent water (<0.05 m/s) while Sonotonics acoustic tags were not detectable in turbulent water but in non-turbulent water could be detected to the bottom (i.e. all depths).

Finally, we investigated depth reading accuracy of both Sonotronics acoustic tags and the ATS DART tags that had been equipped with depth sensors. To accomplish this, we attached tags to a weight, and sunk it to various known depths in calm water. Sonotronics tags were tested once at 9 meters and twice at 13 meters, ATS depth tags were tested once at 4 different depths between 1.5 and 6 meters. Our Sonotronics depth tests read correct Pound per Square Inch (PSI) integer readings for all depths, which when converted to depth in meters, and was within the company specified error range of 1.4 m (+/- .2 m CI which includes variation due to temperature change). ATS depth sensors gave the correct depth within 1 m, with a standard deviation of ±3.8 cm. At LD2, we felt confident in our ability to detect fish only in non-turbulent water. These areas varied with river stages as illustrated in Figure 1.

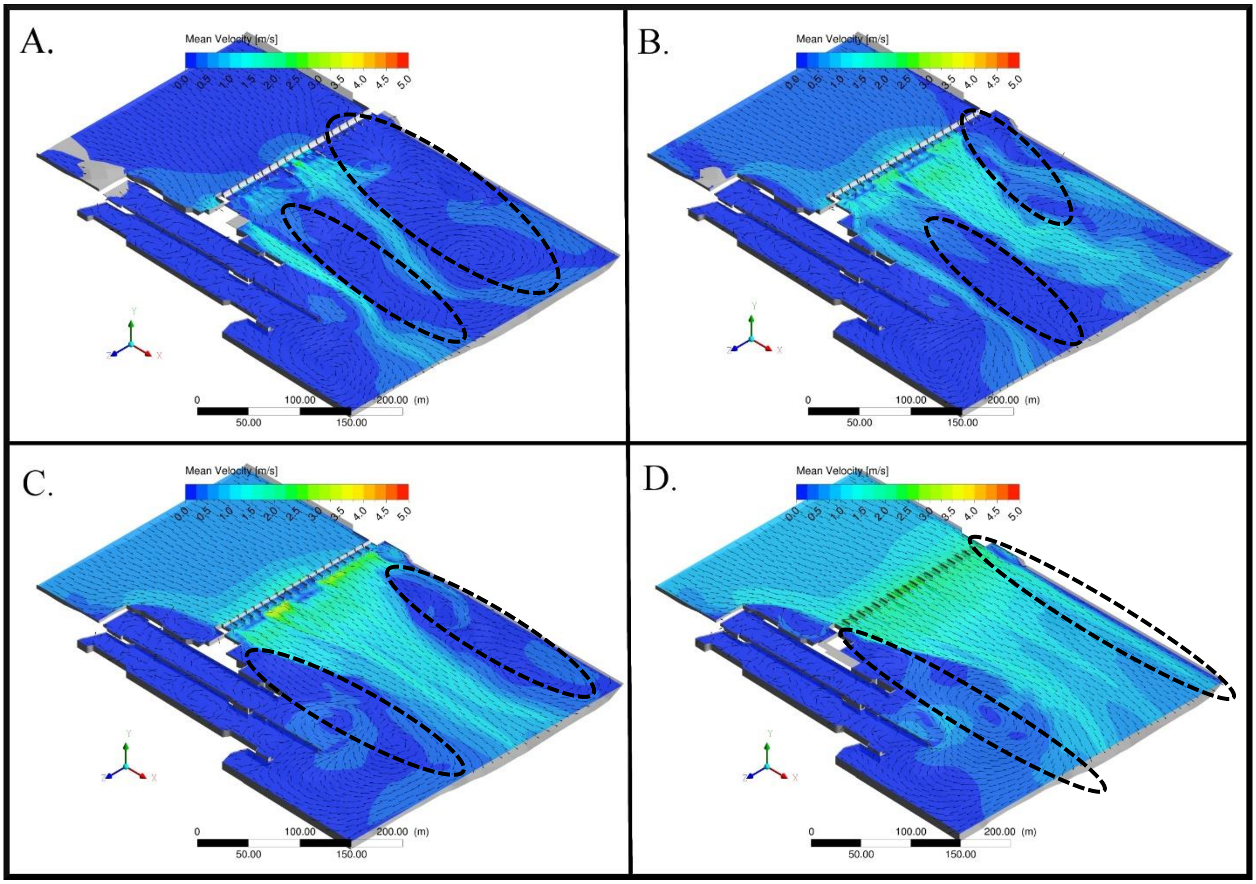


Figure 1 This figure shows the distribution of surface water velocity below the spillway gates of Lock and Dam 2 at different river discharges. The black circles depict areas where we believed that tagged fish were consistently detectable with both radio (up to 4 m deep) and acoustic tags (full depth range).We only felt confident in our ability to detect fish in very low turbulence (calm) areas (<0.5 ms/s; darker blue areas in this figure). A: 13,000 cfs, B: 29,000 cfs, C: 45,000 cfs and D: 61,000 cfs.

3.3.4.3 Locating tagged fish to determine fish distribution below LD2

Fish were located across an 8-position sampling grid during 13 days in 2016, 28 days in 2017, and 11 days in 2018 (Table 2; Figure 2) between the hours of 0900h and 1600h. We traveled by boat and stopped at each position to search for fish using both a radio receiver (R4500SD, ATS) and an acoustic receiver (USR-14, Sonotronics). Tagged fish positions were determined using bi-angulation (Bajer et al. 2010). Once a fish was detected, we recorded the GPS position of the boat and estimated the direction where the fish was relative to the boat (i.e. compass bearing) using an aerial radio antenna (radio) or an underwater hydrophone (acoustic). This step was repeated from two different locations, so the fish position could be calculated as the crossing of two bearings. Once all fish were located at a position, we changed positions. All 8 positions were visited each day when possible. If needed, (e.g. we could not approach the dam due to highly turbulent water) we located fish by standing on the shoreline or LD2 (radio tracking only). Fish were not tracked during open river conditions because of safety concerns associated with high waters.

Fish positions were plotted and grouped by water flow (low; 2000-20000 cfs, medium: 20000-380000 cfs; high: 38000-50000cfs). These flows encompass the range experienced during sampling. These groups of flows were chosen as they coarsely represented the three main spillway gate configurations. Low flow represented cases when only gates 8, 9, 10 and 11 were open (sometimes including 1, 2, 3, 4 barely open: < 2ft). High flow included river discharges when all or most (>= 17 out of 19 gates) were open. Medium flow described river discharges for all other gate configurations. Figure 4d below shows representative flow distributions for these river discharges. Radio and acoustically tagged fish were first plotted separately and then combined (Figure 4a-c below).

Figure 2 The 8-point sampling grid showing the approximate regions visited by boat to search for fish. These locations were chosen to ensure that all areas within 400m downstream of LD2 where fish could potentially be detected were searched.

Table 2 Sampling periods for the different groups of fish studied.

	Pool 2 Common Carp	**Pool 3 Common Carp**	**Pool 2 Channel Catfish**
Radio tracking	Aug 24-2016 to Sep 27-2017	May 18-2017 to June 23-2017	Sep 29-2016 to Sep 27-2017
Acoustic tracking	Aug 24-2017 to June 15-2018	May 29-2018 to June 15-2018	June 5-2018 to Sep 17-2018

3.3.4.4 Quantifying fish swimming paths and approaches at the spillway gates

After we had surveyed the entire sample grid to determine fish distribution, we returned to a position where we had previously detected a fish of interest (i.e. near the spillway gates or approaching them). We then tracked this fish by localizing it every 5 - 20 min to determine a movement track. We followed individuals for 3 h unless we lost them (i.e., no longer able to detect-usually due to turbulence). While tracking fish, we were specifically interested in their tendencies to move upstream toward LD2. We quantified the number of fish detected immediately (within 120 m) downstream of the spillway gates. These detections were termed “approaches.” In addition, we were interested in how long fish remained near the spillway gates (<120 meters). 120 m downstream of the dam was where turbulence noticeably and consistently decreased so this distance became an important benchmark. Only tracks with a duration of 20 min or more (from the first position to the last position) were used for analysis. Radio and acoustically tagged fish were treated identically in this analysis as these fish appeared to behave in the same manners (see below).

3.3.4.5 Quantifying fish swimming depth below LD2

As we tracked fish tagged with Sonotronics (see 3.3.4.1), we noted the depth at which these fish swam. Depth was averaged daily for each individual detected (referred to as depth observation). In addition, we analyzed data from the 8 Pool 2 Common Carp which had been tagged with the DART ATS depth-sensitive tags and whose depths were relayed to archival receivers #2 and #13 in the Fish Passage Study (Figure 3). Depth data was extracted using ATS Trident Series SR5000 and SR3000 software. Depth was averaged on a daily basis for each individual detected (referred to as a depth observation).

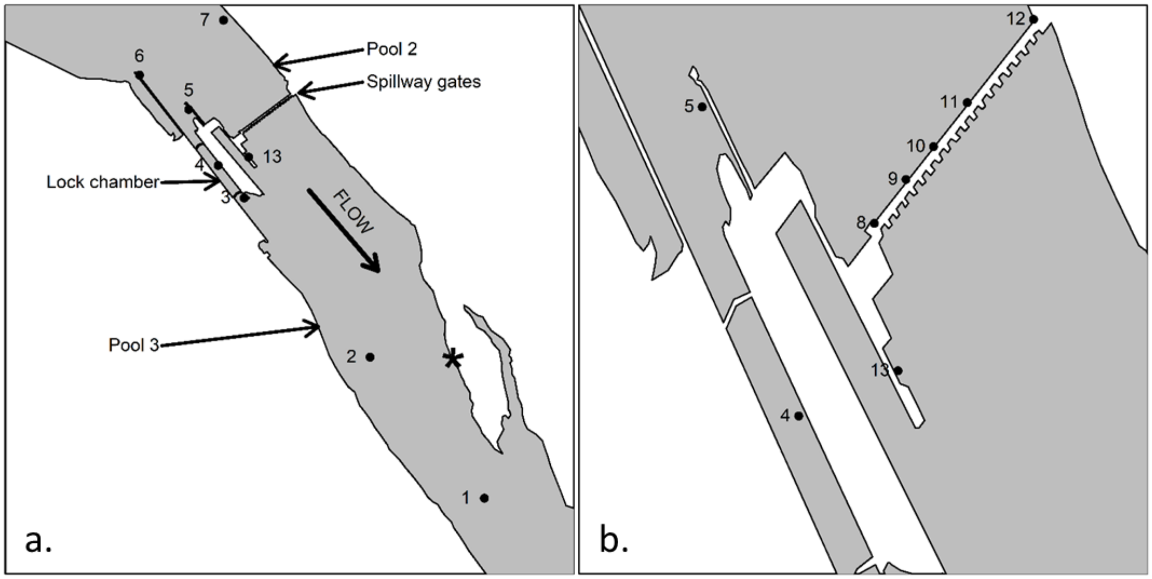


Figure 3 a) Position of acoustic receivers on and around LD2 (* indicates the location of surgeries and release). b) Magnification of LD2 showing the position of spillway gate acoustic receivers (#8 - #12) and receiver #13. Depth data was downloaded from receivers #2 and #13.

3.3.5 RESULTS

3.3.5.1 Distribution of Common Carp and Channel Catfish located below LD2

We collected data from a total of 34 Pool 2 Common Carp, 13 Pool 3 Common Carp and 8 Pool 2 Channel Catfish during 52 days of tracking (Figure 4). These fish were detected a total of 143 times. The distribution of radio and acoustically tagged fish overlapped extensively, so the data were combined. The majority of all detections of both Common Carp and Channel Catfish occurred on the eastern riverbank downstream of LD2, with an especially large number in the northeast corner of Pool 3, just below the spillway gates (67/143). In contrast, fewer fish were detected along the western shoreline of the river (44/143) even though most of this region typically had flow rates of less than 0.5m /sec and we could detect tags at this location with ease. No tags were located in the center of the river within 120 m of the spillway gates. However, Common Carp were commonly located across the width of the river further downstream.

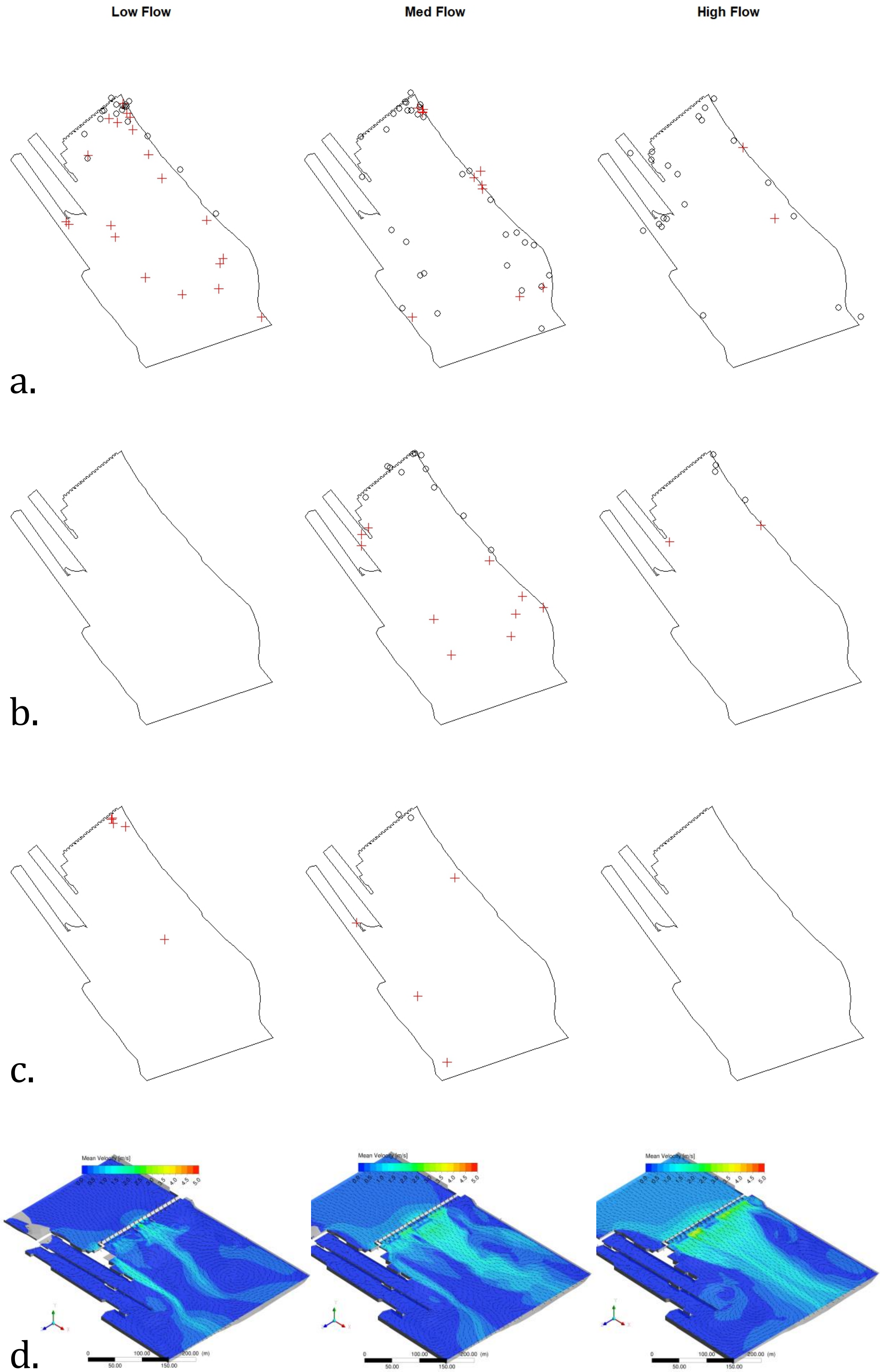

Low Flow
Med Flow
High Flow
a.
b.
c.
d.
Mean Velocity [m/s]
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
0
50.00
100.00
150.00
200.00 (m)

Figure 4 Distribution of fish (a) Pool 2 Common Carp (b) Pool 3 Common Carp and (c) Pool 2 Channel Catfish detected below LD2 in low, medium, and high velocity flows. Black circles represent radio tagged fish positions. Red crosses represent acoustic tagged fish positions. D: water velocities distribution for 13000, 29000 and 45000 cfs at the surface. Surface water velocities were calculated using computational flow dynamics modeling as part of our FPM (Zielinski et al. 2018). Note that the dark blue areas coincide with areas of low turbulence where we felt confident in our ability to detect most fish.

3.3.5.2 Monitoring fish behavior below the spillway gates below LD2

Eleven radio-tagged (16 tracks) and 5 acoustic-tagged (8 tracks) Pool 2 Common Carp, 7 radio-tagged (10 tracks) and 1 acoustic-tagged (1 track) Pool 3 Common Carp, and 4 acoustic-tagged (5 tracks) Pool 2 Channel Catfish were tracked. 15 (7 radio and 8 acoustic) of these 40 tracks were classified as "approaches" (see section 3.3.4.4 above) with 14 (93%) of these occurring along the east side of the spillway gates (Figure 5) and 1 ending by the west side of the spillway gates (Table 3). One fish that arrived by the spillway gates on the east side moved to the west side 90 minutes later. A similar movement pattern was observed in another Pool 2 Common Carp that moved from west to the east in 20 minutes (Figure 5), demonstrating the mobility of these fish in front of the spillway gates. Of these14 approaches that ended on the east side, only 8 approaches started from the east shore. During the 6 other approaches, fish were initially detected away from the east shore (i.e. either along the west shoreline or near the center of the river) before their approaches (Figure 5). We observed 17 events where Pool 2 Common Carp remained near the spillway gates (<120m) for at least 108 min ± 62 min. We also tracked 9 events where Pool 3 Common Carp spent at least 118 min ± 69 min immediately below the gates. We also observed 4 events where Pool 2 Channel Catfish spent at least 143 min ± 72 min below the gates (Table 4). On some occasions the same individuals were detected approaching or staying by the spillway gates on different days (5 Pool 2 Common Carp [2.8 days ± 1.3], 2 Pool 3 Common Carp [2 and 3 days] and 1 Pool 2 Channel Catfish [2days]) (Table 5), indicating repeated approaches by the same individual.

Table 3 Total number of approaches classified by ending position.

	Detected northeast side of the gates	**Detected west side of the gates**
Pool 2 Common Carp	10 (5 radio, 5 acoustic)	1 (radio)
Pool 3 Common Carp	3 (2 radio, 1 acoustic)	0
Pool 2 Channel Catfish	1 (acoustic)	0

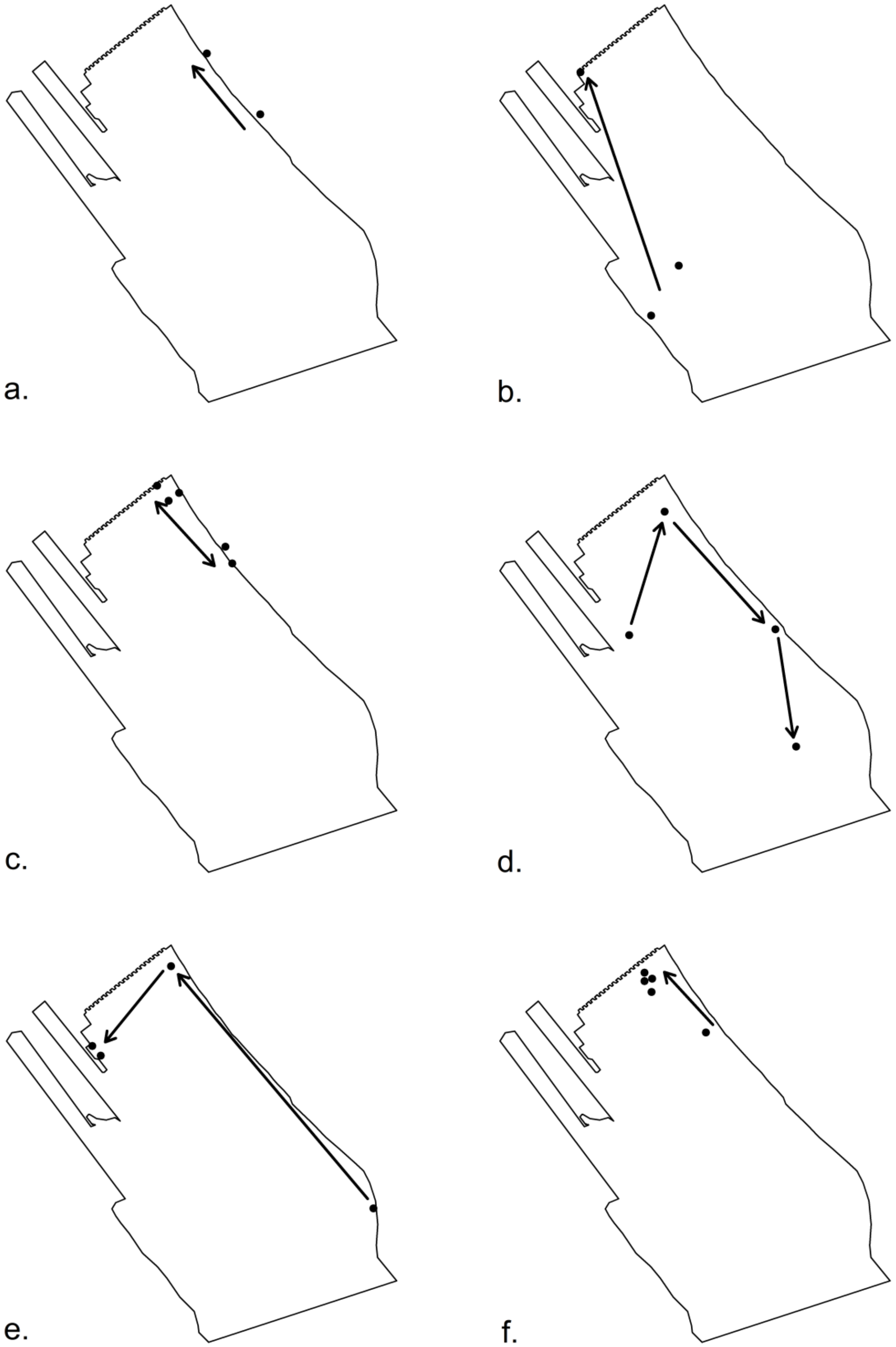
Table 4 Time fish stayed in the same area near the spillway gates (ind= individual)

	Radio	Acoustic
Pool 2 Common Carp	122 min ± 67 (7 ind; N=12)	73 min ± 27 (4 ind; N=5)
Pool 3 Common Carp	118 min ± 69 (7 ind; N=9)	-
Pool 2 Channel Catfish	-	143 min ± 72 (3 ind; N=4)

Table 5 The total number of days the same individuals approached and stayed near the spillway gates.

	Radio	Acoustic
Pool 2 Common Carp	2 ind (5 and 2 days)	3 ind (3, 2 and 2 days)
Pool 3 Common Carp	2 ind (2 and 3 days)	-
Pool 2 Channel Catfish	-	1 ind (2 days)

While tracking fish next to the highly turbulent water created by the spillway gates, we often suddenly lost the signal, suggesting that the fish entered high turbulent water. We observed14 events in which we lost detections while tracking close to these turbulent waters: 7 events for Pool 2 Common Carp, 3 for Pool 2 Common Carp, and 4 for Pool 2 Channel Catfish.


a.
b.
c.
d.
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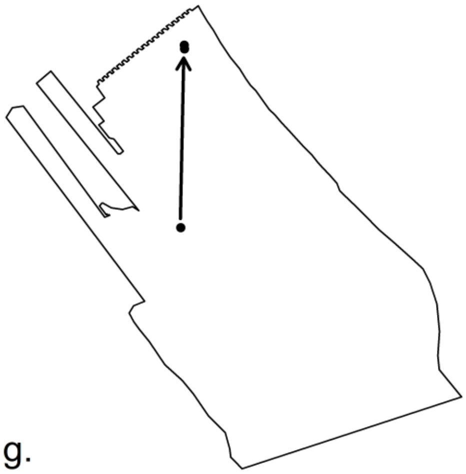

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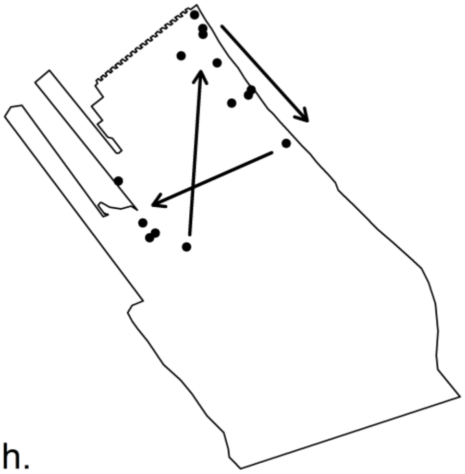

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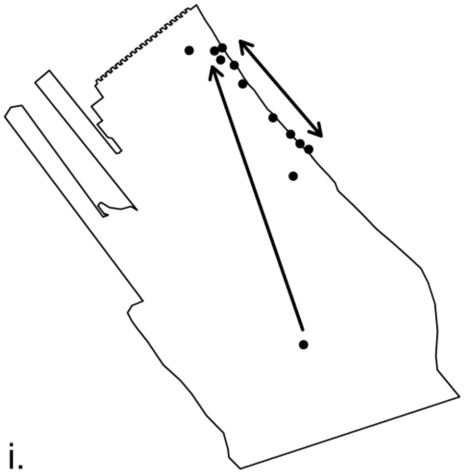

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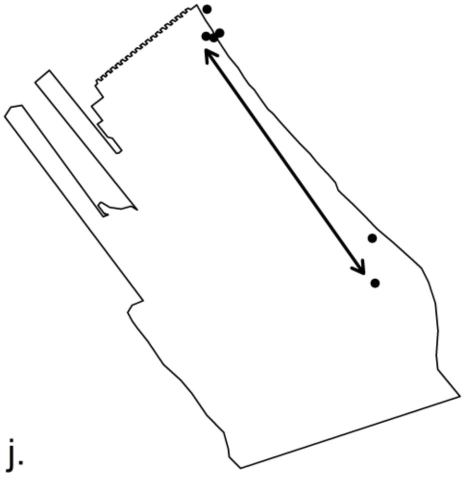

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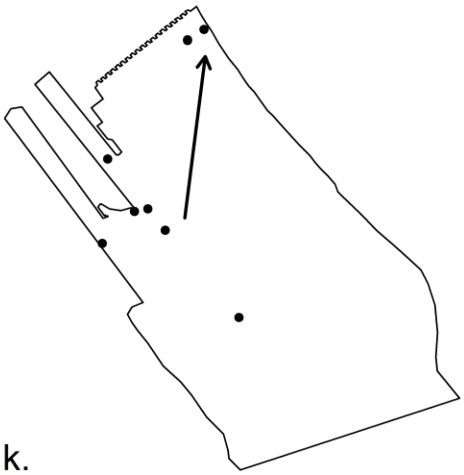

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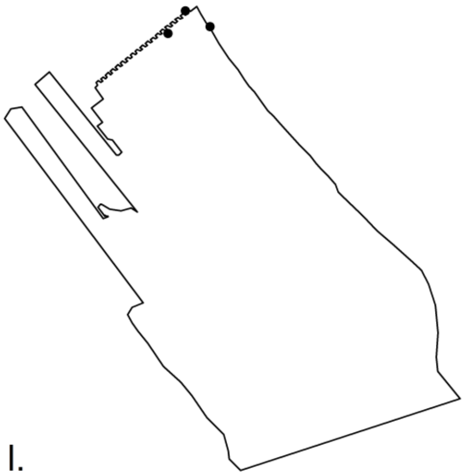

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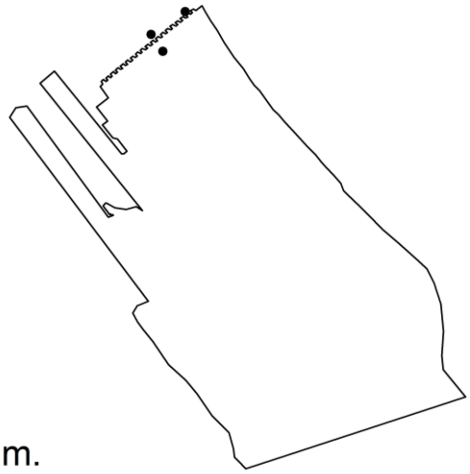
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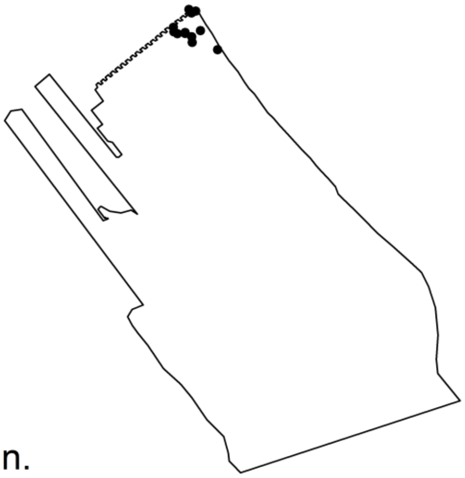
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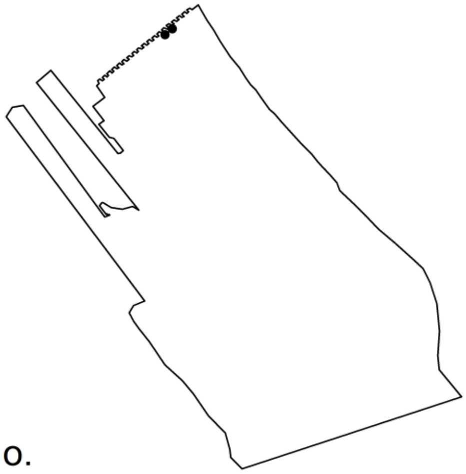
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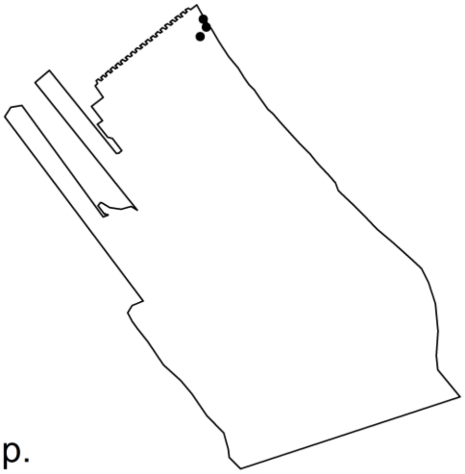
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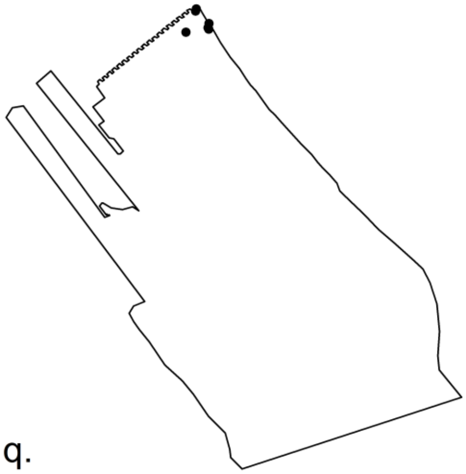
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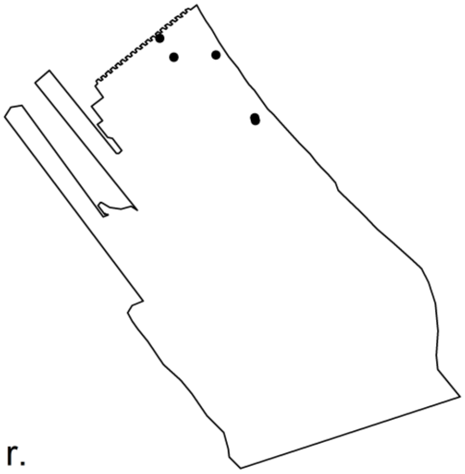
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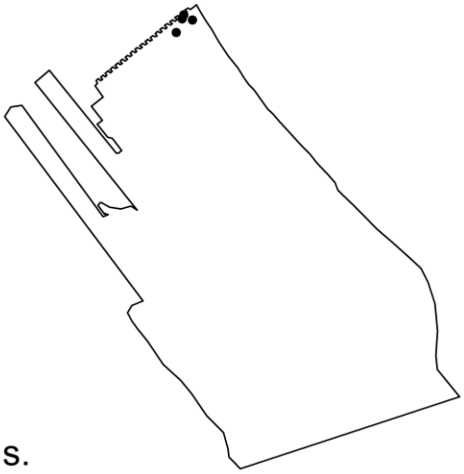

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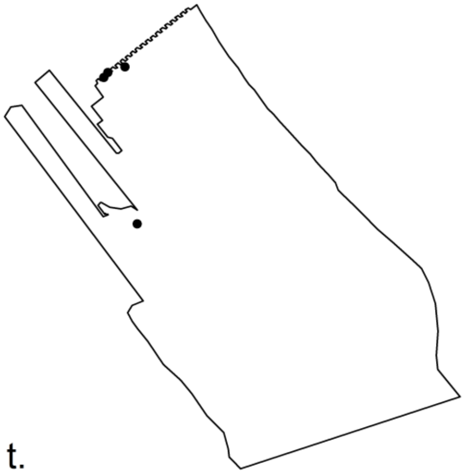

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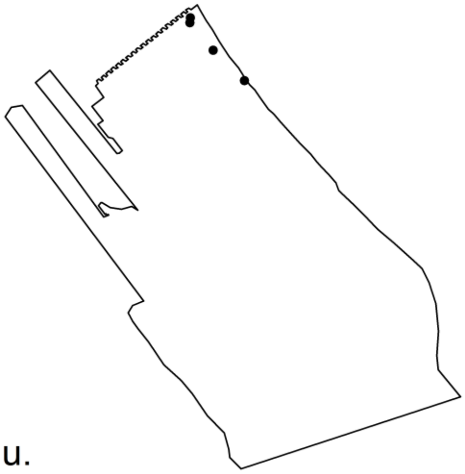

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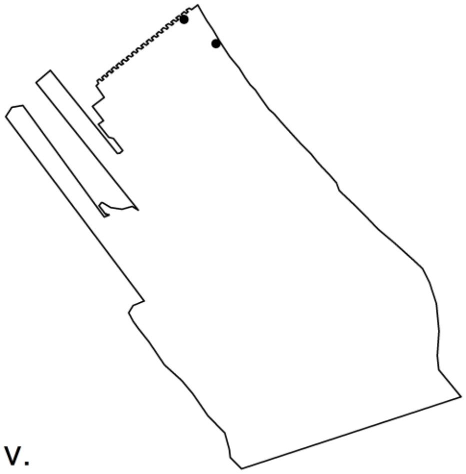

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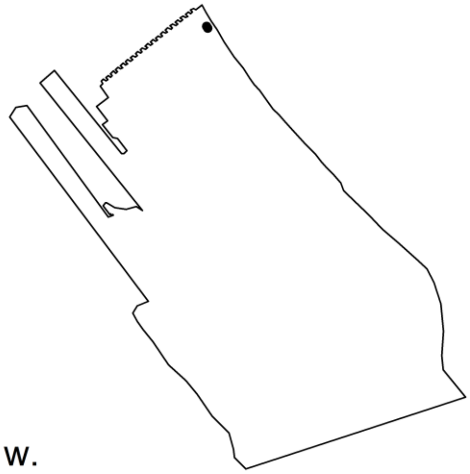

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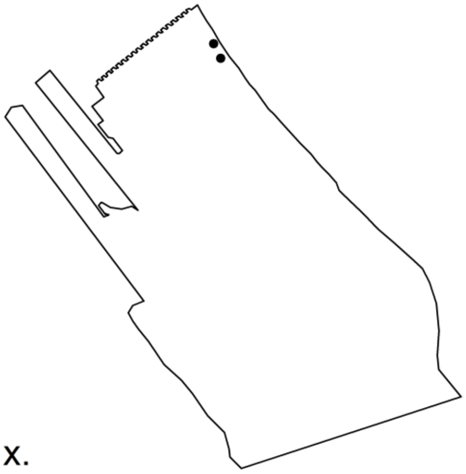

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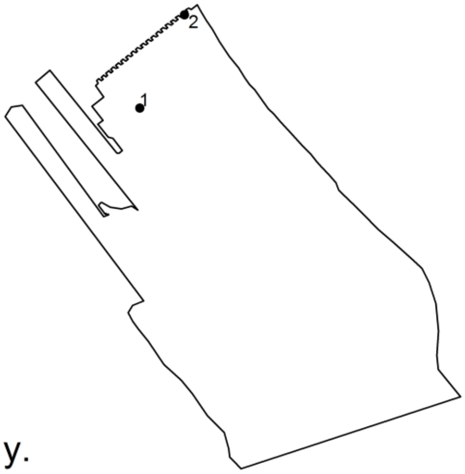

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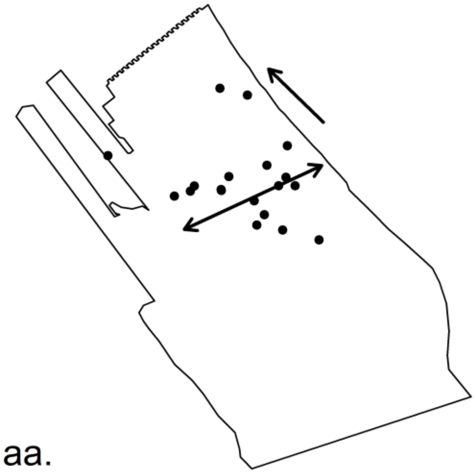

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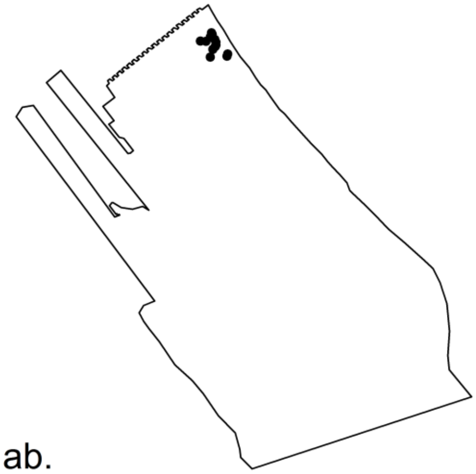

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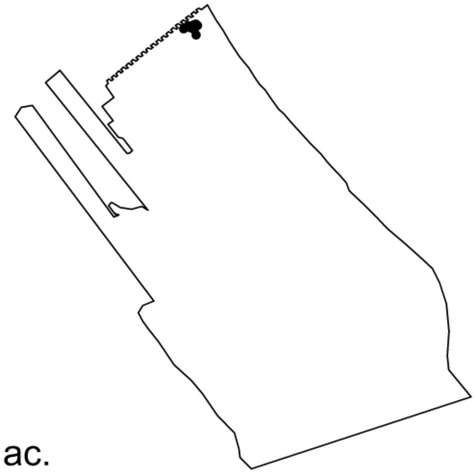

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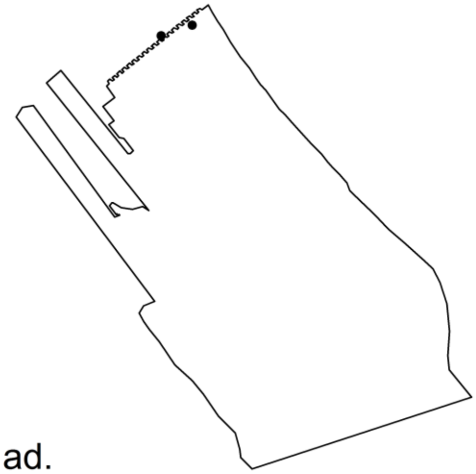

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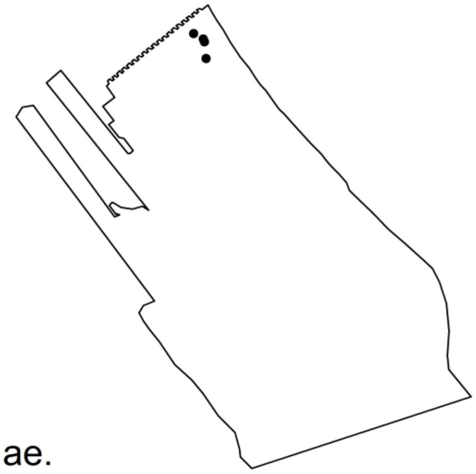


ae.

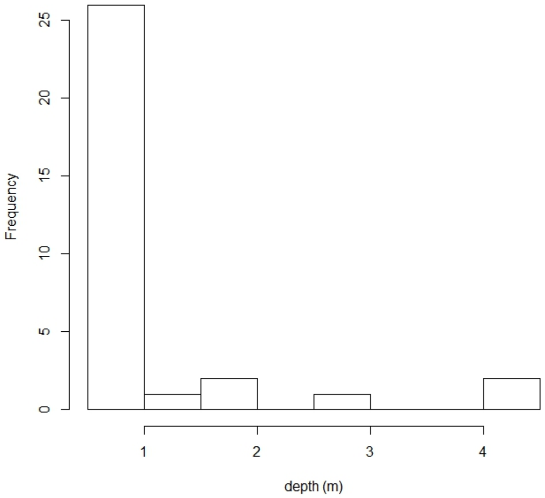
Figure 5 Approaches made by Pool 2 Common Carps toward the spillway gates (a.-k.) detected using radio (a.-e.) and acoustic (f.-k.) tracking. Pool 2 Common Carp were also observed to spend 20 minutes to 3 hours near the spillway gates (l.-x.) using radio (l.-v.) and acoustic (w. and x.) tracking. Some tracks include both an approach and long residence time by the spillway gates (c., f., h., i.). Pool 2 Channel Catfish were only successfully tracked using acoustic technology (aa.-ae.). We only obtained one approach (aa.) and 4 instances of long residence time by the spillway gates (ab.-ae.). Arrows do not show the path taken by the fish; they only indicate the order of location changes. A double-headed arrow illustrates at least one back and forth movement between locations. y. shows the track of a Pool 2 Common Carp that was difficult to class into either approach or long residence time near the spillway gates. This fish was found on the west side of the turbulent water (1) and was detected 20 minutes afterwards on the east side of the turbulent water (2) demonstrating the mobility of this species around the structure.

3.3.5.3 Fish swimming depths

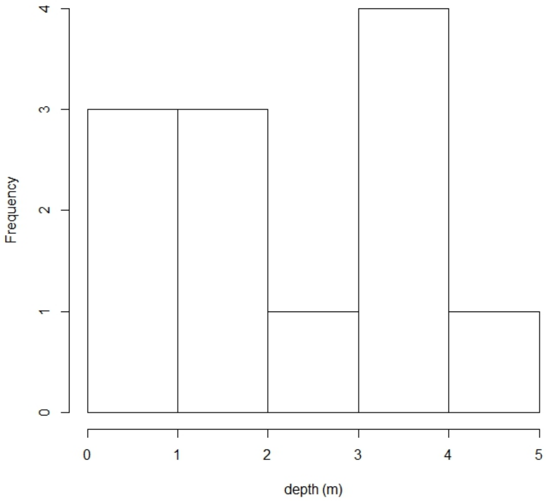
We recorded 32 depths from 10 Pool 2 Common Carp, which swam at an average depth of 1.1 m ± 0.9 m (SE; 84.3% of observations between 0 and 1.5 m; Figure 6). We also recorded 12 depth observations from 4 Pool 3 Common Carp, which swam at an average depth of 2.3 m ± 1.4 m (SE; 33.3 % of observation between 0 and 1.5 m; Figure 6). Of the latter 4 fish, one individual accounted for 6 observations and it never went shallower than 1.5. In addition, we recorded 9 depths for 6 Pool 2 Channel Catfish, which swam at an average depth of 2.4 m ± 1.2 m (SE; 22.2 % observations were between 0 and 1.5 m, med= 2.4, Figure 6).

Pool 2 Common Carp differed from Pool 2 Channel Catfish (Mann-Whitney U test: W=44.5, p-value<0.01) and Pool 3 Common Carp (Mann-Whitney U test: W=73, p-value<0.01) in the depth they were found. Pool 3 Common Carp and Pool 2 Channel Catfish were not significantly different (Mann-Whitney U test: W=57.5, p-value=0.83).

Depth distribution of Pool 2 Common Carp



Depth distribution of Pool 3 Common Carp



Depth distribution of Pool 2 Chanel Catfish

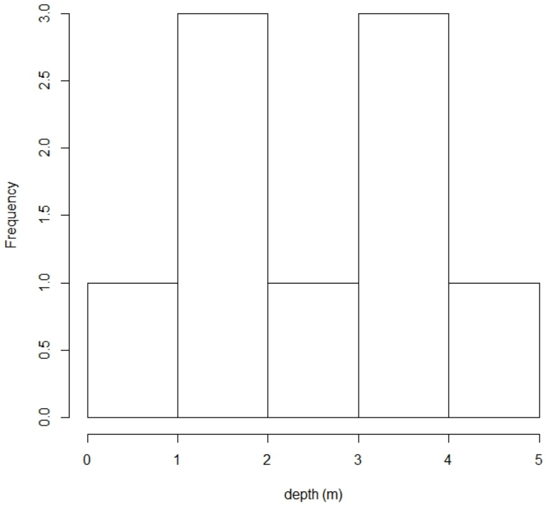
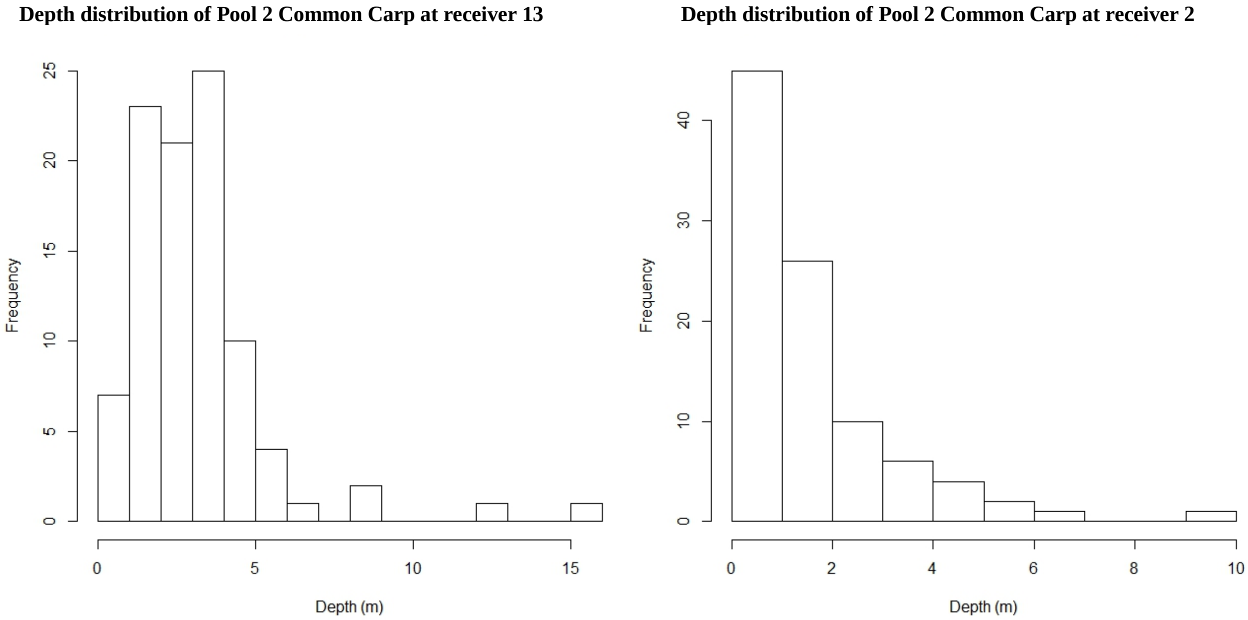


Figure 6 Depth distribution of Pool 2 Common Carp (n= 32 observations, N= 10 individuals), Pool 3 Common Carp (n= 12 observations, N= 4 individuals) and Pool 2 Channel Catfish (n= 9 observations, N= 6 individuals).

Seven Pool 2 Common Carp equipped with ATS DART depth tags were also detected at receivers #2 (river bottom depth = 2 to 9 m; N=95 observations) and #13 (river bottom depth = 5 to 18 m; N=95 observations). At receiver #13, Common Carps were detected at an average depth of 3.1 m ± 2.2 m (Figure 7). At receiver #2, Common Carps were detected at an average depth of 1.6 m ± 1.6 m (63.15 % of observations between 0 and 1.5 m, med= 1.1 m; Figure 7) which was significantly different from receiver #13 (Mann-Whitney U test: W=2160, p-value<0.01).


Depth distribution of Pool 2 Common Carp at receiver 13

Depth distribution of Pool 2 Common Carp at receiver 2

Figure 7 Depth distribution of 7 Pool 2 Common Carp equipped with ATS DART depth tags by archival receivers #13 and #2.

3.3.6 DISCUSSION

Although we were unable to continuously locate and track Common Carp and Channel Catfish across the entire width of the river as they swam upstream towards Lock and Dam 2, we nevertheless describe new and compelling evidence that these fish approached LD2 in deliberate manners and at specific depths. At LD2, fish seemed to end up in the slow-flowing calm waters of the East corner of the dam, where they then appeared to spend at least several hours. In addition, we found that Common Carp tended to swim in the upper portion of the water column whereas Channel Catfish tend to use deeper waters. Common Carp approached the LD mainly via the east river bank, which also happen to be the slowest and then stay in these slower waters for extended periods of time, while challenging them. This new information could be useful to guide management strategies and perhaps develop a new behaviorally-based FPM which calculates actual passage rates rather than a simple index which is known to be an overestimate.

Although we were not able to locate fish across turbulent water areas created by the LD, our study does suggest that fish preferred to swim in certain areas of the river. Common Carp and Channel Catfish were found more frequently along the east side of the river bank. It is unclear whether this is a behavioral preference for the shore or a preference for the areas with the least velocity. Nevertheless, it is interesting to note that even when not approaching form the east shore most Common Carp ended up in the northeast corner. This shows that fish are highly mobile below the spillway gates and suggests that fish may actively search for areas of low flow, where they will stay in for multiple hours. The importance of these observations is further reinforced by the fact that Common Carp approached this area on multiple occasions and on multiple days. This particular behavior is not also addressed in the FPM and we believe that including this behavior into a new FPM might improve predictions of passage. Further analysis of time spent near the LD2 and number approaches is planned as it would be especially insightful.

Another important finding was that Common Carp strongly prefer to swim in the top few meters of the water column when moving upstream and Channel Catfish swim slightly deeper. This is important because water velocity varies with depth so this value strongly influences FPM predictions. However, it is still unclear whether fish swim deeper or remain near the surface when entering the turbulent areas, when attempting to pass the spillway gates. The greater depth of Common Carp measured at receiver #13 supports the possibility that they may go deeper (where the gate opens). These data will be analyzed in greater detail and seek to determine if river depth also influenced depth swam as well as current velocity.

Together, our observations might explain how in our passage study, fish were so efficient at moving through the spillway gates in the 5 brief days of open river conditions (Section 3.2). Clearly, it is important to understand when gates typically open relative to fish migratory patterns. Management responses to this possible challenge might be found by focusing on specific LDs, possibly adding targeted acoustic deterrents to specific spillway gates (in addition to lock chambers), targeted fish removal and perhaps changes in gate operating schedules. Notably, we did not observe any passage during controlled river conditions at LD2, despite fish behavior that might favor fish passage. We believe that as predicted by the FPM, high velocities under the spillway gates was responsible. The FPM was designed to conservatively recognize when fish can pass, not when and how they will if they are capable of doing so – this would require a new model that uses behavioral data such as included here.

In conclusion, we have demonstrated that Common Carp and may be Channel Catfish approach locks and dams in very specific ways that could help describe how fish pass certain lock and dams under certain flow conditions.. This information could be used to guide spillway gate operations to enhance native fish passage or to block invasive carp. If Bigheaded Carp utilize areas below locks and dams the way Common Carp seem to, steps could be taken to prevent passage at time of river (speakers might be added). Although more study is needed, information on fish swimming depth and approach rates could be used to develop a new behaviorally-based FPM (ex. Goodwin et al. 2014) which includes behavioral and physiological variables to estimate actual passage rates rather than a passage index of what is not likely to.

3.3.7 REFERENCES

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4.0 Deliverable #3: Monitoring the ability of an underwater speaker system already mounted on the lock gates at a model lock and dam (Lock and Dam 8, a point north of where Bigheaded Carps are routinely captured is our test site for year 1) to deter native fish and Common Carp (Objective #2).

4.1. INTRODUCTION TO DELIVERABLE #3

We examined the effects of a sound deterrent system mounted on the lock gates of Lock and Dam 8 (LD8) on Common Carp to pass this structure. The Common Carp were tagged with acoustic tags and used as a surrogate species for Bigheaded Carps. We found no discernable effect of the sound we played (an abbreviated outboard motor sound) on either Common Carp passage or the presence of local fishes. A much improved sound systems including a bioacoustic fence are now schedule for field testing. A draft manuscript (management brief) has been prepared in the style of the *North American Journal of Fisheries Management.* We plan to submit this manuscript in 2019.

4.2 DRAFT MANUSCRIPT for the North American Journal of Fisheries Management: A field test of the ability of an outboard boat motor sound to prevent Common Carp from passing through a Mississippi River navigation lock

4.2.1 ABSTRACT

A sound deterrent system was attached to the lock gates of a Mississippi River lock and dam and the tendency of this deterrent to stop the upstream movement of acoustically tagged Common Carp was monitored. The system was only activated when the gates opened for a lockage. No discernable effects of this system was noted on Common Carp or other local fishes, which were monitored by an array of acoustic receivers and by

underwater sonar. It is possible that another type of sound operated in a different way might be more effective.

4.2.2 INTRODUCTION

Developing ways to manage invasive fish is one of the most significant challenges in fisheries management. In the United States, one of the species receiving the greatest attention are the Silver Carp (*Hypophthalmichthys molitrix*) and Bigheaded Carp (*H. nobilis*) (together known as Bigheaded Carp) which are advancing up the Mississippi River and threaten to inhabit the Great Lakes and Upper Mississippi River (Tucker et al. 1996). Recent telemetry studies at locks and dams in the Mississippi River (Tripp et al. 2014; Finger et al. in review) and Illinois River (Lubejko et al. 2017) show that passages occur through both the spillway gates and lock of lock and dam structures. Because some spillway gates operate in ways that preclude most passage (Zielinski et al. 2018; Finger et al. in review.), the navigational locks are of special concern. Recently, behavioral deterrent systems, which utilize aversive stimuli (i.e., sound, light, CO2, bubbles) to block fish in a taxon-specific manner, have been suggested as a means to impede the spread of Bigheaded Carps (Popper and Carlson 1998; Taylor et al. 2003; 2005; Noatch and Suski 2012; Ruebush et al. 2012; Zielinski and Sorensen 2015; 2016). Carps are ostariophysians and have an exceptional sense of hearing, which is superior to that of many native Mississippi River fishes (Lovell et al. 2006; Mann et al. 2007). Studies suggest that sound is a promising deterrent for Common Carp (*Cyprinus carpio*) as well as Bigheaded Carps (Taylor et al. 2005; Sonny et al. 2006; Ruebush et al. 2012; Zielinski et al. 2014; Zielinski and Sorensen 2016) and evidence from many laboratory studies indicate that Common and

Bigheaded Carp actively avoid the broadband sound of an outboard boat motor (Vetter et al. 2015; 2017; Zielinski and Sorensen 2017). Further, Zielinski et al. 2014 shows that Common Carp can be used as a conservative surrogate species for Bigheaded Carp. However, it is currently unknown whether this sound will deter Carp in the field (e.g., Mississippi River). The objective of this study was to test the efficacy of an outboard boat motor sound on Common Carp and native fishes at a Mississippi River lock and dam.

4.2.3 METHODS

4.2.3.1 Study Location

This study took place at Mississippi River Lock and Dam 8 (LD8), Genoa, Wisconsin, USA (43°34’12” N 91°13’54” W) which is Minnesota’s southernmost lock and dam (Figure 1a). LD8 is approximately 250 km north of Pool 14 (southeastern Iowa), which has been suggested as the leading edge of Bigheaded Carp reproduction (Larson et al., 2017). LD8 stretches the entire width of the river (370 m) and consists of 5 roller gates, 10 tainter gates (together referred to as spillway gates), one inoperable auxiliary lock, and one active lock chamber (Figure 1b).

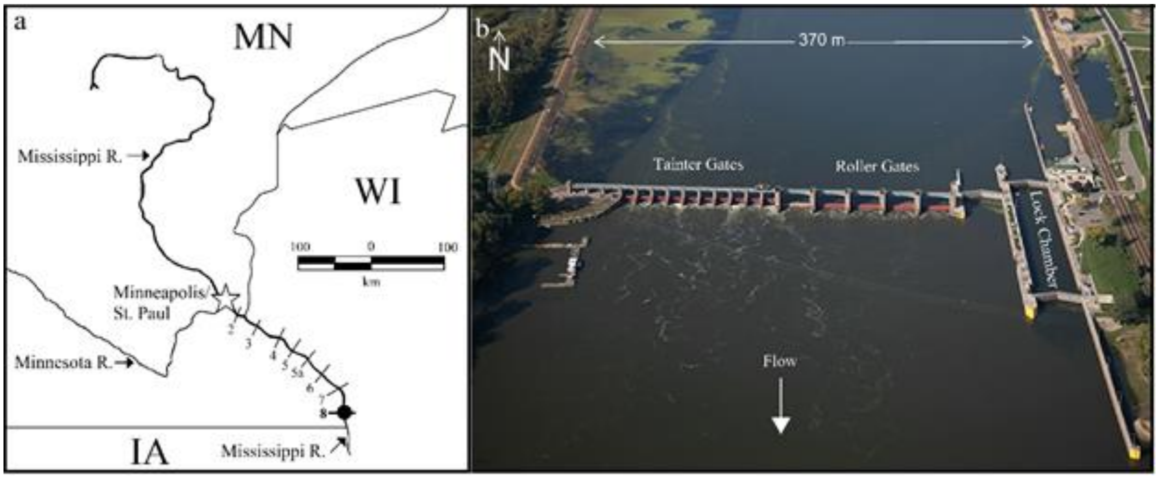


Figure 1. (a) Map showing the locations of navigational lock and dams (represented as bars and labeled by number) on the Mississippi River. (b) Aerial photograph of Lock and Dam 8, Genoa, WI. Photo taken by U.S. Army Corps of Engineers.

4.2.3.2 Acoustic Deterrent System

The acoustic deterrent system had 5 general purpose piezoelectric underwater transducers (LL-1424HP, Lubell Labs, OH) with a usable frequency range of 200-9000 Hz with a maximum sound pressure level (SPL) of 197 dB (ref. 1 µPa). These transducers were activated when the gates were opened and stayed on as long as this was the case. Transducers were attached (evenly staggered at a distance of 5 m) to the south side of the downstream lock gates using stainless steel strut frames and beam clamps mounted to vertical I-beams on the gate. Each transducer was connected to a bridge transformer (AC1424HP, Lubell Labs, OH) and power amplifier (CDi2000, Crown Audio, IN) using 14/3 SO (Seacon, CA) cable. A transmission signal was sent to each amplifier from a signal splitter (Ultralink Pro MX882, Behringer, BVI). The transmission signal sent to the signal splitter was generated from a custom-built micro-processor control unit. The control unit was comprised of an Arduino Uno micro-processor, VS1053 codec and microSD breakout, data logging shield, current monitors, and magnetic reed switch. The micro-processor was programed to play a pre-determined signal (stored on microSD card) and record the current sent to the traducer from opening to closing of the lock gates. Opening and closing of the lock gates were detected with a magnetic reed switch attached to the lock gates and was used to ensure the system only produced sound when the downstream lock gates were open and continued until the gates closed. The sound signal was derived from underwater recordings of a 40 hp outboard boat motor, similar to the signal tested by Zielinski and

Sorensen (2017). This signal is a broadband sound between 500-1500 Hz (Figure 2) and its frequency range is within the most sensitive hearing range (750-1500 Hz) of Bigheaded and Common Carp (Popper 1972; Lovell et al. 2006), yet above the hearing range (< 500 Hz) of many native fish without similar hearing specializations (Ladich and Fay 2013). The system was initially programmed to produce a sound field with sound pressure levels >150 dB (ref. 1 µPa), but concern over interference with barge operation forced the sound source to be reduced to ~140 dB (ref. 1 µPa).

Sound pressure levels were mapped downstream of the gates at a mid-depth (3 m) (Figure 3). Sound pressure measurements were acquired using a CR1 hydrophone [sensitivity: -198.0 dB ref 1V/µPa; usable frequency range: 0.016-68 kHz] (Cetacean Research, Seattle, WA), sampled at 44.1 kHz and digitized using a TASCAM US-122mkII (TEAC, Montebello, CA) USB audio interface. The sound pressure levels peaked at 139 dB (ref. 1 µPa) at 654 Hz measured 1 m from the lock gates and decreased to 108 dB (ref. 1 µPa) 60 m downstream of the lock gates. The ambient sound pressure level was 98 dB (ref. 1 µPa) at 654Hz when the gates were closed and no boat traffic was nearby.

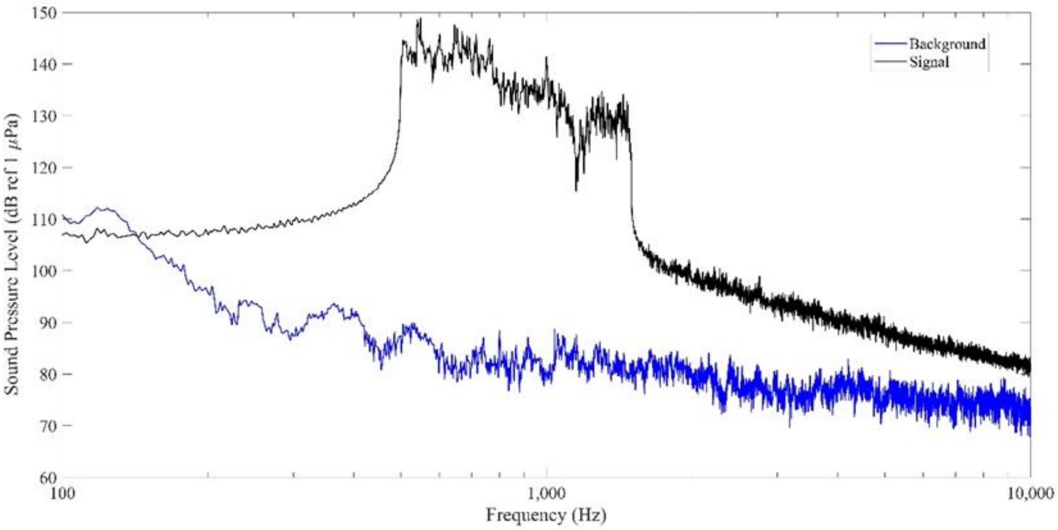


Figure 2: Sound pressure level power spectrum of the background noise and playback signal 1 m from a transducer. Sound pressure level measurements are provided at 1Hz bandwidth.

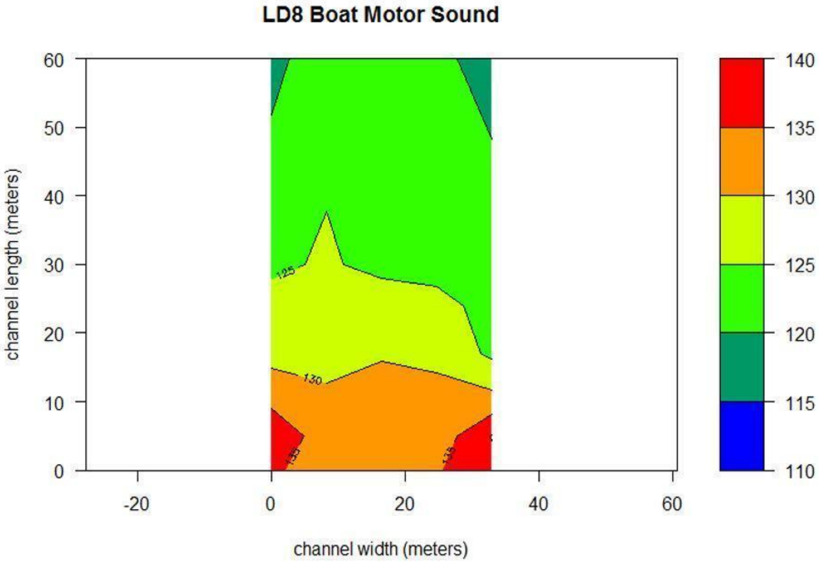


Figure 3: Map of sound pressure levels dB (ref. 1 µPa) between 500-1500 Hz in front of the downstream lock gates when the sound was on and gates on.

4.2.3.3 Experimental Design

This study monitored the passage of Common Carp through this sound deterrent barrier and into the lock (experiment 1) between May and September 2017 and August 2018. We also monitored the presence of fish in front of the lock doors using an ARIS sonar system (experiment 2) in May and June of 2017.

4.2.3.3.1 Experiment 1- displaced Common Carp passage through sound deterrent barrier

This experiment tested the ability of the outboard boat motor sound to block the upstream movement of locally caught and displaced Common Carp at the lock of LD8. We transported and displaced Common Carp because our recent studies at LD2 showed that 13 of 56 adult Common Carp displaced from Pool 2 to Pool 3 passed upstream through the lock within a month. Additionally, Common Carp homing tendencies were observed by Crook (2004) in the Broken River, Australia. We decided to exploit this behavior by displacing Common Carp from Pool 8 to Pool 9 to increase the likelihood of these fish challenging our acoustic deterrent system. Adult Common Carp [total length 671 ± 70.3 mm (mean ± SD)] were collected by electrofishing in Pool 8 (13 km upstream of LD8) and displaced to Pool 9, below the lock. Fish were surgically implanted with an 11 mm SS300 acoustic transmitter (Advanced Telemetry Systems, Isanti, MN) and released 250 m downstream of the lock (Figure 3). During the 2017 field season, six consecutive trials (each lasting 14 days) monitored the movement of tagged Common Carp (20 fish per trial, 6 trials, n = 120). In the summer of 2018 two additional trials were conducted (20 fish per trial, 2 trials, n = 40) following the same methods. To account for variation in environmental and/or fish physiological/behavioral factors (e.g., water temperature, river stage, motivation etc.) the eight trials alternated between sound off and sound on (sound off n = 4, sound on n = 4). Upstream movements were monitored using an array of three submersible SR3000 acoustic receivers (Advanced Telemetry Systems, MN) fastened to recessed ladder wells along the lock chamber (Figure 4). The receiver data was downloaded and analyzed after each trial to determine the rate of entrance (i.e., passage through the acoustic barrier) into the lock chamber. An entrance was considered valid only when an individual fish was simultaneously detected by the three receivers.

Figure 4: Aerial photograph of the lock at Lock and Dam No. 8 depicting the surgery and release site (white X) and acoustic receivers (white dots).

4.2.3.3.2 Experiment 2- local fish presence

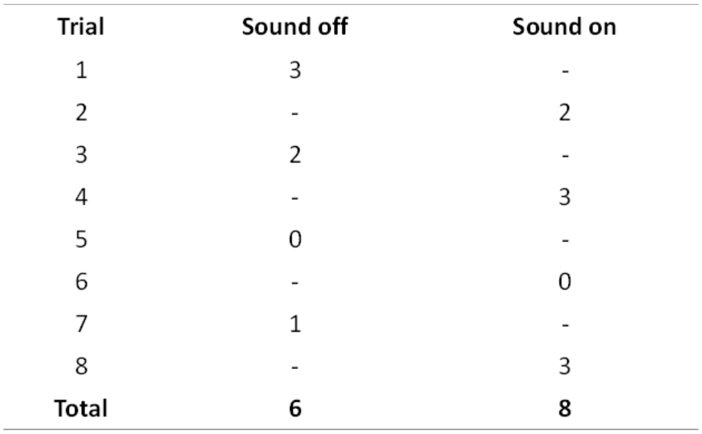
This experiment used an ARIS Explorer 1800 underwater imaging sonar (Sound Metrics, WA, USA) to determine fish abundance in front of the lock gates with the sound off vs. sound on. The ARIS converts sound pulses into digital images, making it possible to observe fish in turbid waters. Eight 20-minute ARIS videos were recorded over a two-day period. Each day, two trials were conducted. Each trial consisted of one 20-min video with the sound off, followed by one 20-min video with the sound on. After the conclusion of a sound on video, a one-hour quiet hiatus was taken to allow fish to return to their normal activity before starting the next trial. Due to many schools of small fish and the difficulty associated with determining the actual number of fish within these schools, only fish greater than or equal to 30 cm were counted.

4.2.4 RESULTS

4.2.4.1 Experiment 1- displaced Common Carp passage through sound deterrent barrier

Of the 160 Common Carp tested (8 groups of 20), 145 (91%) swam upstream from the release point and were detected by an acoustic receiver, indicating motivation to pass through the lock and dam. A total of 14 Common Carp passed upstream through the lock chamber, 6 when the sound was off and 8 when it was on (Table I). There was no significant difference in the rate of entrance/passage between sound off and sound on (Mann-Whitney U Test: W=6, p-value >0.05).

Table I. Number of Common Carp that passed through the lock chamber at Lock and Dam No. 8. There was no significant difference in the rate of entrance/passage between sound off and sound on (Mann-Whitney U Test: W=6, p-value>0.05).



Trial	Sound off	Sound on
1	3	-
2	-	2
3	2	-
4	-	3
5	0	-
6	-	0
7	1	-
8	-	3
Total	**6**	**8**

4.2.4.2 Experiment 2- local fish presence

Using ARIS camera we recorded an average of 122.25 fish (std: 34.61) during the 20-min trials when the sound was off and an average of 121.75 fish (std: 27.42) when the sound was on. The abundance of fish between the two treatments was not significant (Mann-Whitney U Test: W=8, p-value>0.05; Figure 5).

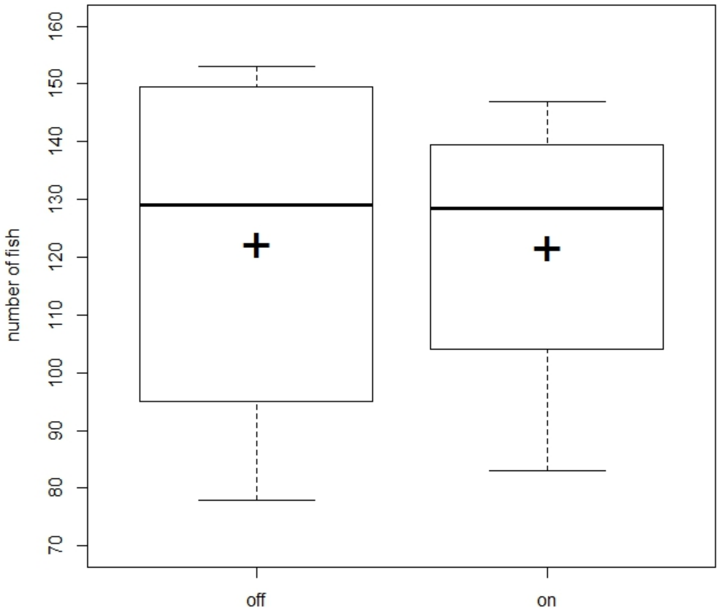


Figure 5. Box and whisker plot depicting the average number of fish observed in front of the lock chamber for each of the four trials. Each trial consisted of two 20-minute ARIS videos (one with sound off and one with sound on).

4.2.3 DISCUSSION

This study showed that playing a 500-1500hz broadband outboard sound system in front of the lock gates of LD8 when it opened was ineffective at blocking the entrance of Common Carp. Similarly, playing this sound seemingly had no effect on the presence of local fish observed by an ARIS camera. There are several reasons why this sound may have been ineffective at this lock. First, as seen in the laboratory with a similar sound (Zielinski and Sorensen 2017), fish may have habituated to this boat motor sound, a possibility that might have been enhanced by boat activity in the area. Second, the sound was only activated when the gates began to open for a lockage, which is likely not optimal because fish were not offered a good opportunity to swim away. Further, the sound field was attenuated when the gates were open. Third, the sound we played was attenuated at both the high and low frequency ranges (to reduce the possibility of damaging the transducers) which may have reduced efficacy. Of course, many of the local fishes (which we tried to sample) were almost certainly not hearing specialists. Future studies will address all three issues addressed by this study by playing a different cyclic sound with a wider spectrum well in advance of gate opening. Responses to this sound do not induce habituation in the laboratory.

4.2.4 ACKNOWLEDGEMENTS

We thank the Minnesota Department of Natural Resources and U.S. Fish and Wildlife (USFWS) for funding this work through a Minnesota Outdoor Heritage Fund allocation and an USFWS grant. We thank USFWS and Jenna Merry for providing their help during fish capture and tagging events. We are also grateful to the WI DNR for their help with permits and fish capture. We thank Clark Dennis III for his help in taking sound measurements and building the sound map.

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5.0 Deliverable #4: Designing and helping to install an underwater speaker system on the lock gates at Lock and Dam 19 in Iowa where its ability to deflect upstream-migrating Silver and Bigheaded Carp will be monitored by the Missouri DNR (Objective #3).

The USFWS was unable to get approval to place speakers at Lock and Dam 19 so this work was not conducted and funds were allocated to Lock and Dam 8 with the consent of the MN DNR.

6.0 EFFORT

Jean-Sebastien Finger and Andy Riesgraf worked full-time (40h/wk with benefits; 100%) on the project and had the help of a part-time undergraduate throughout the field season. In the fall of 2019 Mr. Riesgraf was a MS student. Dr. Sorensen was paid 4 weeks of salary a year for directing the project. The University does not track hours worked because both individuals are employed full time and on salary but we estimated percent time of 40h/ wk for Mr. Finger and Riesgraf as follows:

2016

Project Administration:	*20%*
Establishing tracking techniques:	*10%*
Establishing fish movements:	*15%*
Establishing acoustic array	*15%*
Establishing capture techniques:	*5%*
Tests of Movement Lock and Dam 2:	*30%*
Tests of sound at Lock and Dam 8	*5%*
	$100%

2017

Project administration:	*10%*
Data entering and analysis:	*15%*
Maintenance/downloading acoustic array:	*5%*
Movement tests at LD 2:	*35%*
Passage tests Lock and Dam 2:	*25%*
Passage tests Lock and Dam 8:	*10%*
	100%

2018

Project administration:	*10%*
Data entering and analysis:	*40%*
Maintenance/downloading acoustic array:	*5%*
Movement tests at LD 2:	*15%*
Passage tests Lock and Dam 2:	*20%*
Passage tests Lock and Dam 8:	*10%*
	100%

7.0 BUDGET SUMMARY

Of the $880,000 allocated for this project, $840,000 was spent as of December 2018. Major budget items are as follows rounded to the nearest dollar (Budget statements from the University attached):

Salaries (includes fringe):	*$347,313 (P.I., Postdoc, tech, grad student, undergrad)*
Supplies:	*$174,234(tags, misc. supplies0*
Services:	*$18,665*
Travel:	*$10,185 (to study site, meetings)*
Rent:	*$1,804(boat storage)*
Noncapital equipment:	*$95,370 (specialized depth tags, receivers)*
Capital equipment:	*$106,887(boat, receiver, ARIS)*
Repairs	*$11,702 (boat and receivers)*
Misc	*$0*
Overhead	*$107,530*
TOTAL	*873,690 (rounded)*

$2356 USFWS funds unspent (rounded)
$3,955 returned to the MN DNR unspent

8.0 DATA ARCHIVAL

Data from this study are archived at:
https://conservancy.umn.edu/handle/11299/201400?show=full