2014 Project Abstract
For the Period Ending June 30, 2017

PROJECT TITLE: Blocking Bighead, Silver, and Other Invasive Carp by Optimizing Lock and Dams
PROJECT MANAGER: Peter W. Sorensen
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2014, Chp. 226, Sec. 2, Subd. 04a

APPROPRIATION AMOUNT: $854,000

Overall Project Outcome and Results

We successfully collaborated with the United States Army Corps of Engineers (USACE) and developed new ways and technologies to impede the upstream movement of invasive (bigheaded) carp through their locks and dams in the Mississippi River. Further, these approaches have now been implemented at Lock and Dam #8, which is the southernmost Lock and Dam in Minnesota and has thus been our focus. At this structure, dam spillway gate operating protocols were adjusted by the USACE to optimize their ability to stop carp and speakers added to the lock gates to deter carp with few effects on native fish. This is the first structure in the world to be so modified and our calculations suggest it now stops twice as many carp as it once did (well over 90%). Tentative plans for similar modifications to Lock and Dams #2 and #5 (the other most promising structures in Minnesota) have also been presented to the USACE for future deployment at their discretion. This progress was possible because we met all four objectives of this project: 1) we added speakers to Lock and Dam #1; 2) we quantified and published how well bigheaded carp swim (and thus what flows might stop them); 3) we developed and tested several new acoustic systems in the laboratory and field that stop carp but do not affect native fish ; and 4) we developed new solutions for the gates at Lock and Dam #2-8 and provided specific data (specific solutions) for Locks and Dams #5 and #2, the most promising structures of these.

Project Results Use and Dissemination

Our findings were disseminated via several dozen presentations to both professional scientific and lay groups across both the state and country, as well as four peer-review publications in high quality international journals. The speakers we installed at Lock and Dam #8 are still operating where they stop carp and have inspired the USACE and USFWS to mount similar speaker systems elsewhere while the DNR funded studies of their performance. Meanwhile, the published data we generated on silver and bigheaded carp swimming performance serves as the foundation of computational models to guide changes in gate operations to stop carp. In addition, the sound systems we identified as having special promise for stopping carp are now being considered for installation as part of a proof-of-concept project in both Minnesota (ENRTF, USFWS) and either Illinois or Kentucky (USFWS). Finally, our computational models are guiding gate operations that are presently both stopping carp and reducing scour at Lock and Dam #8. There is active interest by the USFWS to deploy our work downstream to further protect our state and region.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2014 Work Plan Final Report

Date of Report: September 23, 2017

Final Report

Date of Work Plan Approval: June 4, 2014

Project Completion Date: June 30 2017

Does this submission include an amendment request? _N_

PROJECT TITLE: Blocking Bighead, Silver, and Other Invasive Carp by Optimizing Lock and Dams

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Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$854,000**
	Amount Spent:	**$816,116**
	Balance:	**$37,882**

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 04a

Appropriation Language:
$854,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to collaborate with the United States Army Corps of Engineers to develop ways, including new technologies, to modify the operations of Lock and Dam Numbers 2 to 8 to optimize their ability to impede invasive carp movement into the Minnesota, St. Croix, and Mississippi Rivers. This appropriation is available until June 30, 2017, by which time the project must be completed and final products delivered.

Note to reader: Silver (Hypophthalmichthys molitrix) and Bighead carp (H. nobilis) are collectively referred to as "Bigheaded carps" due to the fact that they both belong to the same genus, Hypophthalmichthys. Both of these fishes come from Asia and are invasive in the United States. Rather than use the common term "Asian carp," this proposal uses the more precise and appropriate term of "Bigheaded carp" to refer to these two species collectively. When describing a specific species, this proposal uses the species name.

I. PROJECT TITLE: Blocking Bighead, Silver, and Other Invasive Carp by Optimizing Lock and Dams

II. PROJECT STATEMENT:

Untold millions of invasive Silver and Bighead carp presently inhabit the Mississippi River below the Iowa border from where they threaten to invade Minnesota. This project proposes to solve this problem by developing a scheme to modify lock and dam structures in Minnesota by enhancing their deterent properties through four key, linked steps which are first summarized below and then explained in greater detail:

1) Activity #1 will install a safe carp deterrent in front of the lock at Lock and Dam #8 located at the Iowa border while guiding efforts to enhance and optimize velocity fields to stop carp movement through its gates while having minimal effects on native fishes.
2) Activity #2 will quantify the swimming capabilities of both species of adult Bigheaded carps, thereby producing the data needed to optimize dam function.
3) Activity #3 will identify acoustical deterrent systems that best deter carp from entering lock chambers which have minimal effects on native fishes.
4) Activity #4 will develop numeric solutions to eventually optimize dam operation at all Minnesota lock and dams (#2 through #8) to prevent Bigheaded carp invasion state-wide while having minimal effects on native fishes.

At present, the only impediment to the upstream invasion of Bigheaded carp into the Upper Mississippi River and its tributaries including the Minnesota and St. Croix Rivers are the lock and dams maintained by the US Army Corps of Engineers (USACE) (see Figure 1 for locations of lock and dams). These structures, which stretch the entire width of the river and can be tens of feet tall, function as a relatively complex system to control flows while maintaining constant depth to facilitate navigation. Each lock and dam contains a lock chamber which permits navigation and a series of gated spillways to regulate flow. The USACE is responsible for these structures and has for decades managed them using simple technologies and approaches to maintain minimal flows to reduce velocity and scour. However, the very characteristics that the USACE seeks to maintain (minimal velocity) are exactly those that promote carp passage. Surprisingly, the relatively simple possibility that lock and dam operation might be modified to both maintain their intended function and to deter Bigheaded carp movement has not yet been evaluated. It has generally been assumed that Bigheaded carps can readily traverse the lock and dam structures, yet emerging information on carp swimming performance shows this not to be correct (Hoover, Zielinski and Sorensen, unpublished): slight modifications to lock and dam function which slightly increase velocities to a constant level might hold them back. Recent discussions with the local St. Paul office of the USACE show that it is very willing to seriously consider modifying local lock and dam operations to impede carp movement if this can be accomplished without risking structural integrity, function, or safety (see below). The overarching objective of the project is thus to address the possibility that Minnesota can be spared from an invasion of Bigheaded carps by slightly modifying lock and dam structures and operations while have little effect on native fishes. A longer-term goal is to eventually further modify lock and dam operation to enhance native fish populations while also controlling the Bigheaded carps. This larger objective will require further study in the future. The Mississippi, St. Croix, and Minnesota rivers and their tributaries are invaluable biological resources that must be protected and enhanced for future generations.

The appropriation of $854,000 will be used to accomplish four closely related activities, whose final objective is to make explicit recommendations with (and to) the USACE for optimization of all Minnesota lock and dams (#2 through #8) to block the invasion of Bigheaded carps while still serving USACE needs and having minimal effects in native fishes. Activity #1 seeks to immediately block Bigheaded carps at Lock and Dam #8 (near the Iowa border) by identifying modifications to the gate operations to safely maximize velocities through the dam (higher velocities should deter Bigheaded carps) and installing an acoustic deterrent system, which has special promise but is inexpensive and safe, in its lock chamber. Activity #2 will work with the research arm of the USACE to determine the actual swimming capabilies of adult Bigheaded carps (which have never been formally studied but appear unremarkable), so that they can be factored into optimizing lock and dam function – the USACE does not want higher velocities than absolutely necessary because of risks associated with safety and scour. Activity #3 will test various state-of-the-art acoustic deterrent systems, including water-guns, in a decommissioned lock chamber at Lock and Dam #1 (St. Paul, MN), to determine which might be most effective at repelling carps in a manner that is affordable and acceptable to the USACE and have minimal effects on native fishes. Finally, Activity #4 will apply the swimming performance data collected in Activity #2 with a statistical model of velocities in and around Lock and Dam #2 (Hastings, MN) and adapt a statistical model to identify modifications that might be made to gate operations for the Lock and Dam #2 through #8 in Minnesota to stop carp without causing scouring problems and having minimal effects on native fishes. The USACE has expressed great interest in this project by working with the University of Minnesota and to: 'cooperate …by providing staff support to share data, provide engineering drawings, assist in velocity measurements and participate in technical reviews… and evaluating suggested operational changes … and determining whether they could be implemented without adverse effect to navigation or undue risk to Corps infrastructure.' (R. Snyder, Project Manager USACE, May 31, 2013). Modifying lock and dam function is a safe and cost-effective solution to the 'Asian Carp' problem while having minimal impact on navigation or native fishes (unlike proposed electrical barriers). This project is the first step of a larger plan by Sorensen to eventually improve all fisheries in the Mississippi River by improving how all Minnesota Lock and Dams function though a series of coordinated field and laboratory studies.

III. PROJECT STATUS UPDATES:

Project Status as of 2/28/2015:
The project is making very good progress. For activity #1, a set of 5 underwater speakers has been installed on the gates of Lock and Dam #8 and activated (this activity was partially funded by ENRTF2012). There has been no discernable increase in Bigheaded carp capture north of this location since although our ability to discern such a change is limited.. Modeling of water flow through Lock and Dam #8 is also now well underway and we expect to make recommendations for operational changes to the dam function in August to impede carp movement. For activity #2, work has commenced to determine Bigheaded carp swimming performance via a memorandum of understanding with the U.S. Army Corps of Engineers (USACE) research laboratory in Vicksburg, Mississippi. Although the cold fall has delayed these experiments, no difficulties are expected completing the study in time to generate values needed for the computational flow model. For activity #3, initial work on acoustical deterrents has started in both the field and lab and results are promising. We have rented Auxiliary Lock #1 for experiments and completed initial pilot tests which have described how experiments can be conducted in 2015. Briefly, we have found that we can catch, move and then test common carp in this lock by placing a net at its mouth and tagging fish with ATS acoustical transponders. Sound mapping has also been completed. Additionally, we contracted with Smith Root Inc. (SRI) to gather state-of-the-art information on the possibility of using water-gun and boomer plate technologies in Minnesota locks and dams. Although a final decision has not yet been reached, the SRI report does not describe high promise and we likely will not pursue either of these technologies and may pursue light as a deterrent instead (if we do, an amendment will be needed in August). Finally, laboratory experiments have shown that while carps are repelled by sound in the laboratory, Lake sturgeon are not. We plan to accelerate this project and test Brown trout this winter because the holding facility will be closing this summer for renovations. Work has not yet started for activity #4 as planned.

Project Status as of 9/30/2015:
The project continues to make good progress. For Activity #1, the set of underwater speakers located on the gates of Lock and Dam #8 remains operational and while its affects are not being monitored at present, there has been no statistically discernable increase in bigheaded carp captures north of this location and the MN DNR

is suggesting it will work with the USFWS to fund a new study monitor to ascertain its efficacy. Meanwhile, modeling of water flow through Lock and Dam #8 is nearly complete and starting to evaluate the ability of bigheaded carp to pass through the gates under various conditions. Pilot findings suggest that it likely is possible to block almost all carp with small changes to gate operations. Pilot findings and recommendations have (as proposed) been presented to the USACE which has expressed tentative willingness to make suggested changes in operations. Further meetings and possible announcements are planned. For Activity #2, work to determine adult Bigheaded carp swimming performance has been completed at the USACE research laboratory in Vicksburg, Mississippi. A manuscript is now being prepared and this effort will likely be partially funded by the USACE. For Activity #3, initial work on acoustical deterrents shows promise: while adult common carp were deterred for about 10 minutes by the sound of motorboats in a lock, lake sturgeon were not. Work on additional alternative sound stimuli has been delayed by numerous unexpected challenges and an amendment is now requested to address needed improvements in experimental design for 2016 so the work can proceed efficiently (see below). Based on our experience, we also now propose to test bubble curtain as deterrent but in the laboratory first and with other sounds. Work has not yet started for Activity #4 (as planned). (Note: This report comes one month later than originally planned – and with permission –to allow us to report on the USACE meeting and swimming data).

Amendment Request as of 11/25/2015:
An amendment is requested for Activity #3. We request an amendment to improve the experimental design of our studies which seek to determine the best way to use sounds to deter carps in a lock structure. We have decided not to test hydroguns as work by others (USGS), combined with the report we received from Smith-Root Inc. on this technology, strongly suggest this technology has little promise. Field tests have also proven insightful (outboard motor sound is repulsive) but challenging and suggest that laboratory work to examine different types of sound first would be most productive. Accordingly, we now ask to conduct more tests of different types of sounds in the laboratory (where such tests are easier) and where we also will test the efficacy of a bubble curtain in combination with lights and sounds with assistance from Fish Guidance Systems Ltd., a company that specializes in this technology. Field tests of optimized technologies using sound and bubble curtains are then planned for the field in late 2016 and/or 2017. We ask for funds to be re-budgeted to allow us to conduct this additional laboratory work (more general supplies and nocapital equipment, see below) and subsequent field work. That portion of the re-budget associated with field work will allow us to build a gate in the lock to prevent river otters from taking our experimental fish, to purchase an optimized and automated accoustic tracking system for the lock, for more summer help (the DNR was unable to provide help as originally proposed), to purchase a compressor to produce an air bubble curtain, for repairs (we are now using a 20 year old electrofishing boat we had purchase), and for help from divers and electricians to install the aforementioned. Funds will come from the contract to Smith-Root Inc. which we never awarded (the hydroguns did not prove to be promising) and from the contract to the DNR which we never awarded (they were short-staffed and unable to provide help). Details of the rebudget are shown below.

Personnel:

- Move funds from Scientist to a graduate student position to relect Clark Dennis's new status as a Ph.D. student.
- Add time for a civil service/junior scientist to help in the field (and laboratory) due to DNR being unable to assist with this
- One more week a year of Peter Sorensen's time is required in the summer
- Additional changes were made to accommodate these amendments, which result in a net increase in personnel of $45,172 from $190,773 to $235,945.

Professional/Technical Services and Contracts:

- Increase of $2,000 in general services from $1,000 to $3,000 to allow for more shipping (experimental fish and speakers)

- Increase of $2,000 in lab and medical services from $0 to $2,000 to allow for statistics clinic help
- Decrease of $20,000 professional services and contracts with DNR from $20,000 to $0 to account for DNR no longer being able to provide field tech staffing and a boat
- Increase of $18,000 in professional services & contracts from $0 to $18,000 due to the new need to hire divers to install an air curtain; an electrician to install air curtain; and a technician to build and install a gate for the lock chamber
- Decrease of $1,658 in professional services & contracts from $17,658 to $16,000 to account the cost of the Smith Root Inc. pilot hydrogun test and predesign report being slightly less than expected
- Decrease of $130,993 in professional services & contracts from $130,993 to $0 to account for a redirection of funds away from the Smith Root testing of water guns and boomer plates and to bubble curtains instead
- Increase in $21,661 in professional services & contracts with Fish Guidance Systems from $0 to $21,661 to test bubble curtain technologies in combination with sounds and light using their equipment
- Increase of $2,000 in repairs from $2,000 to $4,000 to pay for additional repairs of equipment, including an old electrofishing boat purchased from DNR with non ENRTF funds
- The total change requested is a net decrease in Professional/Technical Services and Contracts of $106,990 from $171,651 to $64,661.

Supplies, tools, and non capital equipment: With the remodeling of the AIS holding facility we lost use of several custom-built behavioral assay systems and the specialized equipment associated with them (ex. low-light cameras, recording systems, sound production sytems, flow meters, infrared light systems,tracking systems) which could not withstand the stresses of disassembly or simply were no longer suited to the new tanks being supplied as part of the remodel. We now need to replace and rebuild these laboratory assay systems. Additionally, for the field, we also now need piping for a bubble curtain in the auxillary lock, a lap top computer to run this system, and additional field sampling gear because we have to run our own fish sampling program now that the DNR cannot help. Details of these budget changes follow:

Equipment/Tools/Supplies:

- An increase of $1,000 in general supplies from $0 to $1,000 to assist with data collection and analysis
- An increase of $31,446 in supplies- lab & field from $47,054 to $78,500 to acquire: piping for a bubble curtain in the auxiliary lock, new fish, fish food, acoustic tags ($230/ea), etc.
- An increase of $3,709 in Equipment- non capital lab & field from $10,750 to $ 14,459 for a gate for the lock, a bubble curtain fraime, pumps, etc.
- The total change requested is a net increase of $36,155 Equipment/Tools/Supplies from $57,804 to $93,959.

Capital equipment:

- An increase of $19,150 in capital equipment from $33,800 to $52,950 to account for the fact that, while we no longer need PIT tag readers or radio tag receivers, we do need a stationary acoustic monitoring system to track tagged fish in the lock, and a blower to run an air curtain system.

Travel:

An increase of $6,513 in the travel budget from $7,628 to $14,141 to account for the need to rent a truck full time each summer (we discovered the field travel had been greatly underestimated) and for additional travel to workshops and conference to present results and share expertise (our work is attracting attention across the Basin).

Amendment Accepted 12/17/2015

Project Status as of 2/29/2016:

Work is progressing very well. Statistical (CFD) models of water flow-fields through the gates of Lock and Dam #8 have been completed as well as agent-based fish passage models (Activity #1) using the now finalized bighead and silver carp swimming performance data (Activity #2). These models strongly suggest that both bighead and silver carp are largely held back from passing through Lock and Dam #8 by water flow alone and that simple changes in gate operations could enhance this phenomenon without endangering Lock and Dam structural integrity. The USACE has suggested they will implement these changes in gate operating proceedures. Similar modeling work will now start on Lock and Dam #2 and then Lock and Dam #5 which we expect to be even more promising for blocking carps. Final analyses of bighead and silver carp swimming performance data are also now complete and a journal article will be submitted for peer-review by March 15 (Activity #2). Although work with accoustic deterents in the auxiliary lock has proven challenging, it successfully replicated findings in the laboratory and showed that common carp, like bighead and silver carps, are strongly deterred by outboard motor sounds which also do not affect native lake sturgeon. Work will now move to the lab to improve the effectiveness of an optimized sound signal while reducing habituation so we can make recommendations for implementation.

Project Status as of 9/18/2016:
Overall, work is progressing very well; we believe we have identified a workable solution to blocking invasive carp from entering the upper Mississipppi River that involves modifying to gate operations and adding sound deterrents to locks. More data is needed if this scheme is to be implemented so we request an amendment to the present Workplan (as well as to our ENRTF2012 and ENRTF2013 projects – to be submitted later and in a coordinated fashion) at the request of the LCCMR which did not fund a new proposal for this project this year but instead asked that we amend existing projects to get the required data on sound and gate adjustments in the lab (herein). Breifly, Activity #1 of ENRTF2014 is now complete: statistical (CFD) models of water flow-fields through the gates of Lock and Dam #8 have been completed as well as agent-based fish passage models , and recommendations have been made to the US Army Corps of Engineers (USACE) about how to reduce carp passage by changing gate operating protocols. These recommendations were accepted and implemented. Activity #2 is also now complete: bighead and silver carp swimming performance data have also now been collected, analyzed and written up for a peer-reviewed manuscript that is now in press (*Journal of Applied Ichthyology).* Activity #4 is also almost complete; CFD models are complete for Lock and Dam #8 and fish passage models are being now being run. Final results for fish passage and gate operations at this structure will be submitted in the next report by Dr. Zielinski who left the project for a position with greater permanence with the Great Lakes Fishery Commission in Michigan but who will continue to consult for us (subcontract funding is now requested) to ensure completion. Dr. Zielsinki will be replaced by a new PhD engineer who will work with him via this subcontract. For Activity #4, we have also completed initial assessment of weaknesses in other Mississipppi River Lock and Dams and it is evident that gate operations are a weakness to invasive carp passage elsewhere too. However, it is also apparent that new modeling is required to address these issues and that is much more work than we had initially imagined (the structures are more substantial and more different from each other than we had initially thought). Lock and Dams #4 and #5 are of special interest both because of their strategic locations (downstream of Lake Pepin and St Croix River), proximity to each other (they could be employed in a synergistic manner) and because their configurations show they are useful to carp control. Herein, we propose to amend this contract to model Lock and Dam #5 (the most important lock and dam) as part of Activity 4. (An amendment will also later be sought in our ENRTF2012 project to model Lock and Dam #4 in 2017 while its scope will be adjusted). Activity #3 (Accoustical deterrents) is also largely complete (we have strongly recommended that the USACE and DNR consider both sound alone and ideally sound coupled with bubble curtains as an optimal acoustical deterrent for invasive carp at Lock and Dam #5). Meanwhile, funds and time remains as well as the need to optimize sound characteristics needed to stop carp and understand gate operations at locks and dams, and we now propose to conduct key components of this work herein.

Amendment Request as of 10/25/2016:

We request an amendment to add two objectives to Activity #3 to explore the use of different types of sound as a deterrent in the laboratory and to modify an objective for Activity #4 to develop gate modifications at Lock and Dam #5 per the rationale described above and at the request of the LCCMR. To accomplish this, we request the following budget adjustments:

- Decrease in personnel from $235,945 to $225,040 because fewer funds have been needed than previously anticipated
- Decrease in gen oper services from $3000 to $2359 because fewer funds have been needed than previously anticipated
- Decrease in lab & medical services from $2000 to $0 as the super computing institute and statistical services have not been needed as previously anticipated
- Decrease in professional services from $18,000 to $10,000. We will not be hiring the divers, electrician and technician to install the experimental air curtain in the chamber at lock #2 in 2017 as previously planned. We will, however, now need to hire Dr. Dan Zielinski on a contract to continue to assist with this effort by paying for one day a week of his time o he can help with the design of sound signals and share the computer codes he developed for this project (gate adjustments) from his new position in Michigan.
- Decrease in professional services contract with Fish Guidance Systems Ltd. from $21,661 to $14,031, as the cost of the work in the first half of 2017 are less than budgeted (the remaining portion of th contract will be fudned by ENRTF2013 once rebudgeted) .
- Increase in lab and field supplies from $78,500 to $84,274 in order to purchase additional fish that will be used to test the experimental Fish Guidance Systems Ltd deterrent system in the lab (we had originally planned more field work)
- Increase in repairs from $4,000 to $4,335 to account for anticipated need for repairs to lab equipment.
- Increase in non-capital equipment cost from $14,459 to $21,789 in order to purchase a hydrophone and accelerometer to evaluate fish response to the Fish Guidance System Ltd's leased air and sound deterrent system in the lab
- Decrease in capital equipment cost from $52,950 to $42,950 because costs have been lower than expected and we don't anticipate needing any additional equipment because of the change to lab work.
- Decrease in domestic travel from $9,141 to $4,334 and increase in out of state travel from $5,000 to $8,812 to accommodate travel and lodging needed by conultants including Dr. Zielinski between Minnesota and his new position in Michigan and Fish Guidance Systems Ltd.

We also request an amendment to add an objective to Activity #4 to model fish passage and gate operations at Lock and Dam #5 per the rationale described above in the project update. This will entail moving the $7,714 unspent funds from the completed Activity #1 and the $5,379 unspent funds from completed Activity #2 to Activity #4. The resulting balances for Activity #1 and Activity #2 would be $0. The resulting budget changes to Activity #4 would be needed:

- Increase in Personnel from $89,854 to $121,073 to account for an additional 1 week of summer salary for Dr. Sorensen and 3 weeks summery salary for Dr. Vaughan Voller. Dr. Voller will be assisting Dr. Anvar Gilmanov who will be hired to replace (and work with) Dr. Dan Zielinski. Dr. Gilmanov will be coming from the U of MN Saint Anthony Falls Laboratory.
- Decrease in budgets for gen oper services and lab& medical services so that the balances are drawn down to zero.
- Increase in the professional services budget from $0 to $5,000 so we can hire Dan Zielinski on subcontract to continue to assist (1day/wk) with this effort by sharing and explaining custom computer codes and finishing work on Lock and Dam #2 from his new position in Michigan.

- Increase in Gen oper supplies from $0 to $1,000 to cover costs for the new employee, Dr. Gilmanov, to set up his work station and lab area.
- Similarly, increase in non-capital equipment by $2,000 to pay for a new computer for Dr. Gilmanov (Dr. Zielinskis' computer has been transferred to another MAISRC researcher working with Dr. Sorensen). All computers will be retained for continued use by MAISRC staff at the end of project duration.
- Increase in state travel from $672 to $1,000 to allow for one researcher (Dr. Gilmanov)to attend and present at a conference
- Increase in out of state travel from $2,500 to $3,014 to allow for for one researcher to attend and present at a conference

Additional outcomes have been added to the respective areas in IV Project Activites and Outcomes, below to refectt hse changes in scope.

Amendment Approved as of 10/27/2016

Project Status as of 2/28/2017:

The project is going very well. All major goals as defined by the recent amendment are being met. Activity #1 and #2 have been successfully completed. Activity #3 is now examining the abilities of several complex sounds to deter carp in the laboratory. We are using a small model system leased from Fish Guidance Systems Ltd. (FGS) and have thoroughly tested 3 different complex sounds on common carp. The FGS sound is the best of these sounds and it is able to consistently deter almost 90% of all carp in the laboratory setting with even greater effects suggested in pilot studies that have paired it with an air curtain. Similar but seemingly stronger effects are being noted in ongoing experiments using bigheaded (invasive) carps. The study will next complete these experiments with bigheaded carps and examine changing temporal patterning of sound by this June when this project concludes. A amendment proposed for ENRTF2013 might then allow us to examine light as a deterrent and the responses of a few native fishes, after which a final year is needed to complete analyses for all lab work. Activity #4 is also progressing extremely well. The statistical model for Lock and Dam #2 is complete and simulations suggest very low carp passage at this structure (conservatively and typically below 15%) and that these rates could be reduced by about half (or more) by adjusting gate operations in manners that the USACE should find acceptable because they would not increase scour. Modeling of Lock and Dam #5 has commenced and we plan to finish it when this project is complete this June.

Project Status as of 6/30/2017:

The project is now complete and all elements of all four activities have been completed. During the course of the past 6 months, we focused on 1) testing the effects of sound with different temporal patterns on carp deterrents (Activity 3); 2) developing a numeric solutions for optimizing gate operations to stop carp at Lock and Dams #2-#8 with a recent emphasis on Lock and Dam #5 (the key structure for our state; Activity 4). A set of sweeping sounds with 2Hz and 4Hz pulse rates have been identified that can stop almost 95% of all invasive and common carp in the laboratory. Work now continues (ENRTF2013) to determine how further improvements might be made with minimal impact on native fishes. Numeric models of Lock and Dam #5 carp passage and ways to reduce it by altering gate operations have also now been completed. It appears that we can reduce carp passage by at least 50% overall from present levels and a meeting is now being scheduled with the USACE to discuss and implement The USACE formally approved our recommended gate operations table for Lock and Dam #8 this month. It is expected to reduce carp upstream movement by over 50-60% at that location on Minnesota's southern border.

Overall Project Outcomes and Results:

We successfully collaborated with the United States Army Corps of Engineers (USACE) and developed new ways and technologies to impede the upstream movement of invasive (bigheaded) carp through their locks and dams in the Mississippi River. Further, these approaches have now been implemented at Lock and Dam #8, which is the southernmost Lock and Dam in Minnesota and has thus been our focus. At this structure, dam spillway gate operating protocols were adjusted by the USACE to optimize their ability to stop carp and speakers added to the lock gates to deter carp with few effects on native fish. This is the first structure in the world to be so modified and our calculations suggest it now stops twice as many carp as it once did (well over 90%). Tentative plans for similar modifications to Lock and Dams #2 and #5 (the other most promising structures in Minnesota) have also been presented to the USACE for future deployment at their discretion. This progress was possible because we met all four objectives of this project: 1) we added speakers to Lock and Dam #1; 2) we quantified and published how well bigheaded carp swim (and thus what flows might stop them); 3) we developed and tested several new acoustic systems in the laboratory and field that stop carp but do not affect native fish ; and 4) we developed new solutions for the gates at Lock and Dam #2-8 and provided specific data (specific solutions) for Locks and Dams #5 and #2, the most promising structures of these.

Key outcomes are as follows:

Activity 1. Immediate Development and Implementation of a Deterrent Strategy for Lock and Dam #8.

An accoustical deterent system was developed and mounted on the gates of the navigation lock of Lock and Dam #8 while lock operations were modeled and ways to reduce carp passage by at least 50% from starting levels identified, and implemented by the USACE. The accoustic system has meanwhile been broadcasting deterrent sounds for the past three years and has served as a model for other efforts across the entire Mississipppi River Basin. The site has been visited by several DNRs, USFWS, USGS and others; also, its presence is now accepted by the USACE. Presently, the MN DNR is funding its operation and for a study of its effects on carp and other fish (results not available yet).

Activity 2. Quantify Adult Bigheaded Carps Swimming Capabilities

A set of swimming performance experiments were completed with the USACE using adult silver and bighead carp. High quality data were published in a peer-reviwed journal and are now being used in our numeric models of carp passage (see below). These efforts are attracting attention from across the country.

Activity 3. Test and Develop New Accoustical Deterrent Systems for Locks that Deter Carp and Have Minimal Effects on Native Fishes.

We have tested over half a dozen different sounds on several species of carp as well as several native fish species in both the laboratory and field. We have identified a set of sweeping, pulsed sounds with great promise that stop about 95% of all carp (common, silver and bigheaded) without habituation and seemingly has little effect on native fish (bass) If combined with air curtains, efficiancy of the sound is increased further to about 99% in the lab. Field results to date have support those from the lab. We continue to pursue and improve this pulsed sound in the lab (ENRTF2013) while asking for funds to test it in the field. The USFWS has offered to support this proof-of-concept study.

Activity 4. Develop Solutions to Address Weaknesses in Lock and Dam #2 and then Optimize Gate Operation for Lock and Dams #2 through #8.

Our numeric model was used to examine possible invasive carp passage at both Lock and Dam #2 and Lock and Dam #5, the structures of greatest concern in Minnesota waters of the Upper Mississipppi River. This work complemented earlier work on lock and Dam #8. Passage rates at Lock and Dam #2 appear very low; this possibility is now being confirmed by a DNR-funded common carp tracking study. Computational modelling is also complete for Lock and Dam #5. Here, we see great promise to improve the ability of this key structure (below Lake Pepin) to greatly decrease current adult carp passage rates by over another 50%. Work is now starting on Lock and Dam #4 (ENRTF2012), the last of the key structures, while we plan to meet the USACE next month about implementing recommendations for Lock and Dam #5.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Immediate Development and Implementation of a Deterrent Strategy for Lock and Dam #8

Description: The goal of this activity is to immediately and safely maximize water velocity through the gates of Lock and Dam #8 near the Iowa border while deploying a simple and safe acoustical deterrent system in its lock chamber as a stop-gap measure. Stopping Bigheaded carps at this location is critical because once they move north, there are no good options to stop their further advance. Although several Bigheaded carps have been caught north of Lock and Dam #8 over the past 15 years, there is no indication of biologically-significant infestation or reproduction although their eggs were recently sampled below this location. This action is timely and might start before July 1, 2014 using funds from ongoing MAISRC projects. Work will proceed in several steps. First, we will install an array of acoustical deterrents (high-frequency underwater transducers [i.e. sophisticated speakers]) to prevent Bigheaded carp movement through the lock chamber. These devises, which are the highest amplitude sound devices we can obtain and afford, will be placed into extant slots in the lock chamber by divers who will also be guided by the USACE. Next, a 3-dimensional statistical model (computational fluid dynamics [CFD] model) will be developed on the University supercomputer to calculate velocities in and around the structure under a wide range of environmental (temperature, river discharge, etc.) and operational conditions. Data provided by our partner, the USACE, will be used to validate the model. We will then identify changes to gate operation to safely maximize velocity through the gates because we assume that high velocities deter Bigheaded carps. Finally, we will optimize gate function by developing a novel computational tool to search through 3-D flow data from the CFD model, identify potential passageways (specific paths that fish might swim) through the dam, and pair these data with swimming capabilities of Bigheaded carps (Activity #2) to determine if successful passage is possible under varying conditions and then, if appropriate, how to stop it without increasing scour. Models would then be re-run to examine possible effects on native fish passage in a biologically meaningful manner. Limited time and resources restrict us to use two species as models for native fish in this initial project. Given this limitation, we need species that reflect a range of abilities and for which both swimming data and hearing thresholds are already available or can easily be obtained. Accordingly, Lake sturgeon (*Acipenser fulvescens*) and Brown trout (*Salmo trutta*) will be used since the swimming abilities of these fish are: 1) already well established (i.e.we do not need to collect new data and extant data can be easily integrated into the computer model) and represent the spectrum of fish swimming abilities (while the former has modest swimming abilties and is of special interest in the Mississippi River, the latter is able to maintain aerobic high swim speeds), and 2) both are available from hatcheries and/or wild fisheries for tests of deterent species-specificity (Activity #3). Notably, the swimming abilities of Lake Sturgeon are similar to another important native, the Shovelnose sturgeon (*Scaphirhynchus platorynchus*).. Although not of particular importance in the Mississippi River, the Brown trout was selected as a model species that represents the upper range of swimming abilities that are very similar to the native Brook trout (*Salevelinus fontinalis*), an important salmonid. Model results of Brown trout passage will be used to gauge the upper limit of fish swimming abilities on proposed gate modifications. Model results of sturgeon passage will be used to gauge the lower limit of fish swimming abilities on proposed gate modifications. Both Lake sturgeon and Brown trout are found in the vicinity of Lock and Dam #8. With assistance from the USACE, we will maintain and operate the deterrent system in Lock and Dam #8 during the 2015 and 2016 shipping season. The performance of this deterrent system on native and invasive fishes will also be evaluated as part of Activity #3 and by the U.S. Fish and Wildlife Service (USFWS) who have agreed to place monitoring stations in the vicinity for tagged native fish for us.

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$134,050**
	Amount Spent:	**$134,049**
	Balance:	**$1**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
***1a**. Install acoustic deterrent array in lock chamber* ***1b.** Develop and validate computer model of Lock and Dam #8*	February, 2015	$59,276
2. *Make recommendations to USACE to improve gate operation at #8*	August, 2015	$42,492
***3**. Make recommendations to USACE to optimize gate operation at #8 using data from Bigheaded carp and native fish (Lake sturgeon and Brown trout)*	February, 2016	$39,996

Activity Status as of 2/28/2015:

Work is well underway. Initial work was funded by activity #8 in ENRTF2012 where detailed results may also be found as a final report in that project's work plan. Briefly, we installed an array of 5 underwater transducers to the downstream face of the downstream lock chamber gates at Lock and Dam #8 (Genoa, WI) in July 2014. It operated all summer without problems and there has been no discernable increase in Bigheaded carp capture above this location although our ability to monitor this is very limited. Further improvements may be made to the system in the future based on laboratory and field scale experiments presented conducted in the auxiliary lock chamber at Lock and Dam #1 (Activity #3). Also,we are currently seeking out opportunities to actively monitor the effectiveness of the system (USFWS may assist with side-scan sonar surveys of the lock chamber). The speakers are presently off and we anticipate turning them on with ice off in April.

Work is also underway developing a computational model that can simulate passage of Bigheaded carp and native fish through the gated portion of Lock and Dam #8. We began this work by constructing a computer model of the lock and dam structure using engineering drawings and bathymetry data provided by the US Army Corps of Engineers (USACE). This information was used to create a 3D computational fluid dynamics model (CFD) using University super computing resources to calculate the velocities and turbulence characteristics of flow through and around the structure. The CFD model presently contains over 19 million elements and provides velocity data extending ~1500 ft up- and down-stream of the dam structure. We are presently validating the model solutions using 3D velocity measurements obtained by the USACE for 5 different river discharge and gate operation conditions. We have also begun to develop and test a novel algorithm that searches through the velocity field, calculated by the CFD model, to identify the swimming pathways that require the least amount of energy for fish to pass through the dam. This model allows us to identify changes to gate operation that will stop this movement without increasing scour (erosion of river bed) and minimally impact desirable native fish passage. We are on schedule to make initial recommendations on changes to gate operation to maximize velocities without increasing scour (thereby slowing carp movement) to the USACE in August 2015.

Activity Status as of 9/30/2015:

Work is on schedule. Computational fluid dynamics (CFD) models of Lock and Dam #8 at three representative river discharges (Low: 634 m^3/s, Moderate: 2324 m^3/s, and High: 2718 m^3/s) have been run (Fig. 1.1A). These results have been validated using river velocity data provided by the USACE. Computer models suggest current operating conditions do not create uniform velocity distributions across the dam. Uniform velocity distributions are desirable at the dam for two reasons: 1) they maximize velocities across the dam, reducing the potential for low velocity gaps that carp might carp exploit, and 2) they simultaneously minimize turbulence that may increase scour. Our models suggest that minor modifications to the gate openings (< 1' change in gate opening) would redistribute the velocities and create a uniform velocity barrier that could stop carp passage. Modifications of this nature would not exceed downstream velocity limits imposed by the USACE to reduce the risk of scour. A summary of these findings with recommended gate operation modifications for Lock and Dam #8 was presented to the USACE – St. Paul District Water Control Office on Auguest 31, 2015 for consideration of possible implementation. The MN DNR was also present. The USACE expressed significant interest in the CFD models to estimate discharge ratings for each gate, as they were aware of errors in their estimates. They also expressed a willingness to seriously consider implementing the modifications we proposed. Additional meetings are now planned as the dateset is completed.

Work is also ahead of schedule to develop a swimming fatigue and pathway selection algorithm which can be used to determine the percent likelihood of carp thatpass locks and dam through the gated portions of the dam. The model works by seeding simulated fish downstream of the dam and then allowing them to search through the velocity field (CFD results) to identify the least energetically costly pathway through the dam. The model also incorporates turbulent fluctuations (variations in local velocities) produced by flow moving through the structure to more accurately reflect the stochastisity of real flow conditions at the dam. To ensure conservative estimates, we are assuming each simulated fish is optimally driven to move upstream (i.e. no-backtracking) and swims at the theoretically optimum ground covering speed. The swimming fatigue and pathway selection algorithm moves through has four major steps:

1). Locate all upstream neighboring nodes (those located 1-3 body length away from the fish)
2). Calculate the resultant velocity at each node (i.e. velocities in the direction of movement aid passage)
3). Calculate the % Fatigue for each node (i.e. how much of allotted energy does it take)
4). Move fish to node with minimum % Fatigue and start over

The search continues until the fish reaches 100% Fatigue (at which point the fish is assumed to be swept back downstream) or it successfully passes upstream. A Monte Carlo simulation (i.e. simulate N > 1000 fish) then provides both an estimate of the likelihood carp can pass at a given discharge and operating condition and highlight locations at the dam where passage is most likely and where changes to gate operation are needed. An example result of the model for the high flow condition is provided in Figure 1.1. Note, high flow condition has the lowest velocities through the dam because the head differential between headwater and Tailwater is at a minimum. Using preliminary swimming performance data from Activity #2, we presently expect 80 ± 16 % of silver carp arealready unable to pass upstream through the dam under these worse case scenaros (i.e. high flows and no gate modifications). The majority of successful passages also occurs near the outer gates, likely due to slow velocities that persist near the shore downstream of the dam which allow carp to get closer to the dam without fatigue. Currently, these results are preliminary, but final results using silver and bighead carp swimming data from Activity #2 and known native fish swimming capabilities (i.e. Lake Sturgeon) will be reported in the next update.

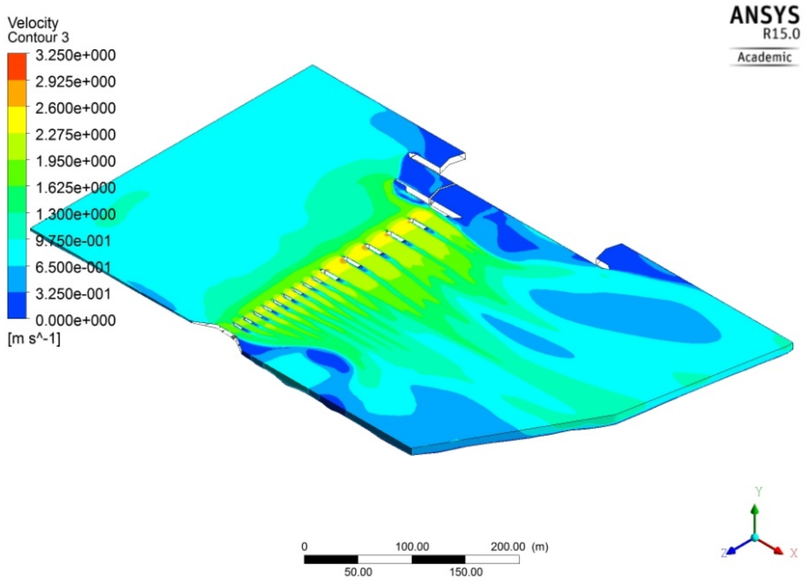


Figure 1.1. (Top) Velocity magnitude contours at the water surface through Lock and Dam #8 at high flow (CFD results), and (Bottom) Monte Carlo simulation of N=100 simulated Silver carp attempting to pass upstream the dam. Less than 20% of the carp pass under the worse case scenario. Red arrows indicate locations where passage is most likely and a possible focus for remediation.

Activity Status as of 2/29/2016:

Work is on schedule is 95+% complete. A final report will be summited in August and work has now started for Activity #4 to examine similar issues at Lock and Dam #2 (and then Lock and dam #5). Results are promising and show that very few bighead or silver carp can pass Lock and Dam #8 and that these passage rates could be reduced by changing gate operaitons in ways that the USACE should find acceptable. Briefly, computational Fluid Dynamics (CFD) models have now been prepared for 7 different river discharges, corresponding to velocity measurements obtained by the USACE in the field with Acoustic Doppler Current Profiler (ADCP) surveys and a physical model study (Markussen and Wilheims, 1987) at Lock and Dam #8 . Analysis of CFD simulations revealed non-uniform velocity distributions downstream of the dam across all flows. Velocities through the roller gate portion exceeded expected ranges by 12%, while velocities through the tainter gate portion were 22% lower than expected. As detailed previously (Activity Status 8/31/2015), non-uniform velocity distributions can adversely increase river bed erosion around the dam and provide low velocity regions fish can exploit to pass the dam. We have determined that adjustments to gate operations that shift ~10% of the discharge volume from the roller gates to the tainter gates, resulting in < 1' changes in gate opening across all gates, produces nearly uniform velocity distributions downstream of the dam. On 08/31/2015 we presented these findings to the USACE district office. The recommendations were well received and the changes to gate operation were tentatively accepted for implementation in 2016.

Our initial recommendations were based solely on velocity conditions through the dam, and were not based on physiological limitations of Bigheaded carp swimming. To quantify the impact gate modifications will have on passage of Bigheaded carp through the dam, we recently developed an agent-based fish passage model (previously described a "swimming fatigue and pathway selection model"). The fish passage model combines CFD models of fluid flow in and around the lock and dam structures with empirical swimming-fatigue relationships to simulate how and where fish might pass assuming fish will move at an distance maximizing speed and seek the path of least resistance, a worse-case scenario. Results from the model indicate the likelihood of passage (i.e. quantitative analysis of all fish) for a given size of fish and highlights what locations fish may pass through the dam (i.e. visual inspection of fish pathways). Simulations were performed for 4 representative flow conditions between 634-2718 m^3/s (both existing and modified gate operations), using finalized Bigheaded carp swimming data, collected by Jan Hoover (see details in Activity #2). Each simulation used N=10,000 fish of each species to attempt passage through the dam. Size ranges for Silver carp ranged from 500-1000 mm total length (TL), and Bighead carp ranged from 600-1100 mm TL. As a demonstration, we present CFD results and Silver carp passage model simulations (N=100 fish for clarity) for a river discharge of 2324 m^3/s under existing and modified gate operation conditions (Figure 1-2 & 1-3). Results in Figure 1-2 and 1-3 are representative of all flow conditions. Under existing operating conditions, both species passed disproportionately more through the tainter gate section than the roller gate section. Modified gate operations generally reduced the overall number of fish expected to pass and limited passage through the tainter gate section. For each river discharge and species, we generated length-dependent likelihood of passage estimates. Using the same river discharge; the likelihood of passage estimates for both Silver and Bighead carp illustrate a substantial reduction in passage across all size ranges.

Population level passage rates were then calculated by multiplying the length-dependent passage estimates with a length distribution expected for a population of Bigheaded carp in the river. Conservatively, we chose the length distributions for Silver carp that had the largest mean total length (data from the Wabash River, Seibert et al., 2015), while the Bighead carp length distribution from the Missouri River (Schrank and Guy,

2002) was the only distribution available. Table 1. Provides the global likelihood of passage for Silver and Bighead carp under 4 existing gate operation conditions and 3 modified gate operation conditions. Due to the limited swimming abilities of Bighead carp, Silver carp passage is greater under all conditions, but still expected to be less than 18%. Overall, ~50% of passage of Silver and Bighead carp can be stopped through the minor gate operation modifications we recommended to the USACE. Simulations are underway to assess potential impacts on native fish species. The fish passage model is being run for lake sturgeon (*Acipenser fulvescens*), a native migratory fish of importance and well documented swimming abilities. The size range of lake sturgeon used in the model was 1000-1400 mm TL. All simulations are expected to be complete by the end of March 2016. Final analyses are now being run and will be complete within a month. For the next update we will present the final report and likely request an amendment and rebudget to redistribute residual funds to close the account and assist with work on Activity #4. Work on Activity #4 has now started on schedule.

Table 1. Population level passage estimates at Lock and Dam #8 for Silver and Bighead carp under existing and modified gate operations.

River Discharge	Silver carp passage		Bighead carp passage	
(m^3/s)	Existing	Modified	Existing	Modified
634	n.a	n.a	n.a	n.a.
1472	5.4%	3.6%	1.8%	n.a
2324	13%	8%	1.2%	0.7%
2718 (open-river)	14%	NA	5.1%	NA

n.a. available until March

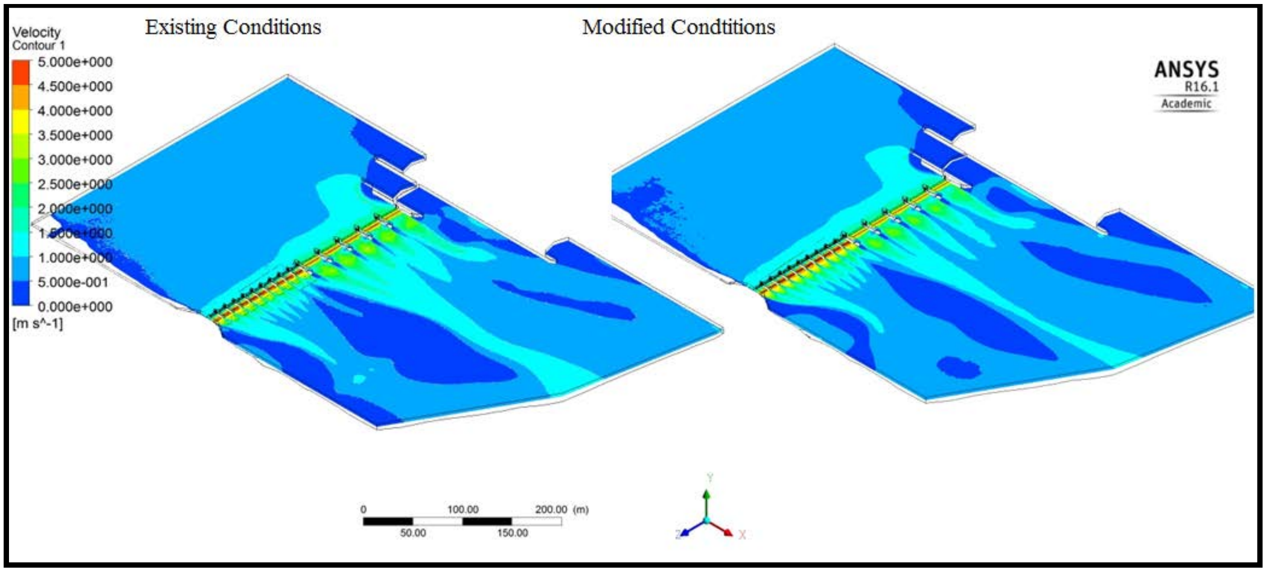


Figure 1-2. Velocity magnitude contours at the water surface through Lock and Dam #8 at river discharge 2324 m^3/s under (left) existing and (right) modified gate operations.

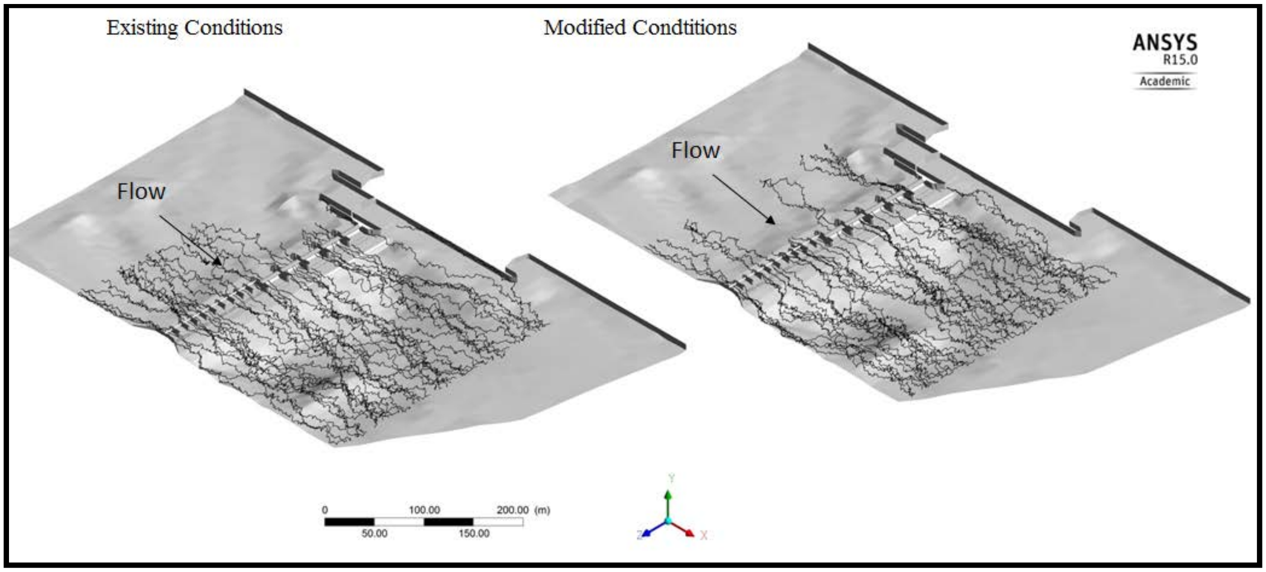


Figure 1-3. N=100 simulated Silver carp pathways up to and through Lock and Dam #8 at river discharge 2324 m^3/s under (left) existing and (right) modified gate operations.

Final Report Summary:

An experimental acoustic deterrent system was installed in the lock chamber at Lock and Dam #8, and has been operating for the past 2 yr without issue. Laboratory studies indicate it is about 70% effective at stopping carp. Computer models of fluid flow in and around Lock and Dam #8 and simulations of fish passage were conducted in order to identify if and how Bigheaded carp pass through the structure and what changes to gate operation will block Bigheaded carp but have minimal impact on native species. To accomplish this, we developed a novel agent-based fish passage model that simulates fish passage assuming fish follow the pathway of least energetic cost. Using this model we were able to calculate the maximum likelihood of passage of various species including silver carp, bighead carp, and lake sturgeon. Our modelling efforts revealed a slight imbalance in flows through the tainter and roller gates, and through modest modifications to gate operation can safely reduce Bigheaded carp passage from 20% to < 10% at all gate controlled flows. We presented recommended gate operations for Lock and Dam #8 to further impede bigheaded carp passage to the St. Paul district office of the USACE. These recommendations were implemented after approval by the Chicago Office of the USACE at Lock and Dam #8 in August 2016. This research has been presented a several regional, national, and international scientific conferences including: American Fisheries Society (AFS) 2015 & 2016, Minnesota AFS 2016, Fish Passage 2015 & 2016, and the 2016 Midwest Fish and Wildlife Conference. Manuscripts detailing this work are in preparation for Ecological Modelling and Science.

ACTIVITY 2: Quantify Adult Bigheaded Carps Swimming Capabilities

Description: Swimming performance data for adult carps are essential to accurately forecast passage and optimize gate function so that velocities are not higher than they needed (i.e. minimize scour). Although these data are available for juvenile Bigheaded carps (Hoover *et al.,* 2012), they are currently not available for adults and the USACE has no plans to collect them as they are not needed at the Chicago barrier for protecting the Great Lakes. The USACE research facility in Vicksburg (MS) is the only U.S. laboratory with the equipment (large swim tunnels) and expertise (Dr. Jan Hoover) needed to address this critical data gap. Swim speed-fatigue curves for a range of velocities, temperatures, and adult sizes of both species will be generated. Data will be collected during cool water temperatures (10±2°C) in the winter and warm water temperatures (25±2°C) in the summer, as swimming performance varies with water temperature. These experiments will provide essential relationships for modeling hypothetical Bigheaded carp passage through lock and dam structures (last step in Activity #1 and Activity #4), and thus how to block it. The Hoover lab will function as a partner and subcontractor. This laboratory has already generated promising preliminary data for the University of Minnesota using internal USACE funding.

Summary Budget Information for Activity 2:	**ENRTF Budget:**	**$151,075**
	Amount Spent:	**$151,075**
	Balance:	**$0**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. *Evaluate swimming ability of Bigheaded carps at high temperatures*	February, 2015	$78,227
2. *Evaluate swimming ability of Bigheaded carps at low temperatures*	August, 2015	$78,227

Activity Status as of 2/28/2015:
A memorandum of understanding (MOU) has been established with the U.S. Army Corps of Engineers (USACE) in Vicksburg, Mississippi to conduct large scale swimming performance tests with adult Bigheaded carps to generate data needed in the computational flow dynamics (CFD) models that will allow us to determine how lock and dam function might be modified to inhibit carp movement (Activities #1 and #4). Dr. Jan Hoover will do the work. While we had initially hoped to do the warm water tests first and have the data available by March 2015, the cold weather this fall has delayed tests so the cool water work will be completed first this winter and then the warm water work by late summer. This delay will not be problem. This work has not yet been billed.

Activity Status as of 9/30/2015:
Work is on schedule. Swimming performance tests of adult silver and bighead carp have been completed by Dr. Jan Hoover at the US Army Corps of Engineers Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi. Tests were conducted in March and June 2015 with average water temperatures of 10°C and 25°C using a total of 17 bighead carp (Total Length: 908 ± 67 mm) and 54 silver carp (Total Length: 803 ± 69 mm). The mobile swim tunnel (90 cm H x 90 cm W x 240 cm L) was transported to the shoreline of Forest Home Chute, a side channel of the Mississippi River. Fish were caught with gill nets and tested within 30 mins of capture. Once acclimatized to the swim tunnel, responsive fish (those that actively swam) were subjected to a single water velocity and the time that the fish were able to maintain position in the tank was recorded. Time-to-Fatigue curves were then generated using swim speeds normalized by fish body length (Figure 2.1 and 2.2). Overall, the swimming performance of both silver and bighead carp were rather average (i.e. no better than most fish andseemingly typical of fish that evolved in slow flowing water). Silver carp swimming abilities were slightly higher than bighead carp, and cool water swim speeds tended to be higher than in warm water. The data can now be used in conjunction with the swimming fatigue and pathway selection model described in Activity #1. A final report with additional analysis of swimming performance data based on fish size, gender, age, and reproductive stage will be supplied by Dr. Jan Hoover in the fall of 2015. A manuscript for peer review is also being prepared.

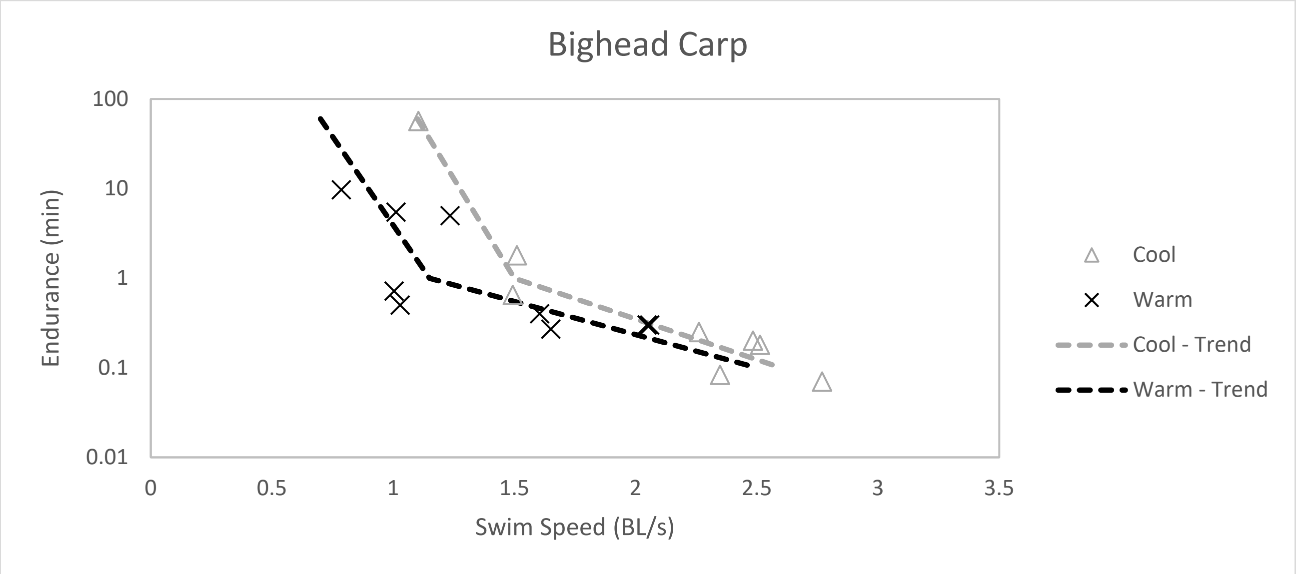


Figure 2.1. Time-to-fatigue curve for Bighead carp at cool (10°C) and warm (25°C) water temperatures.

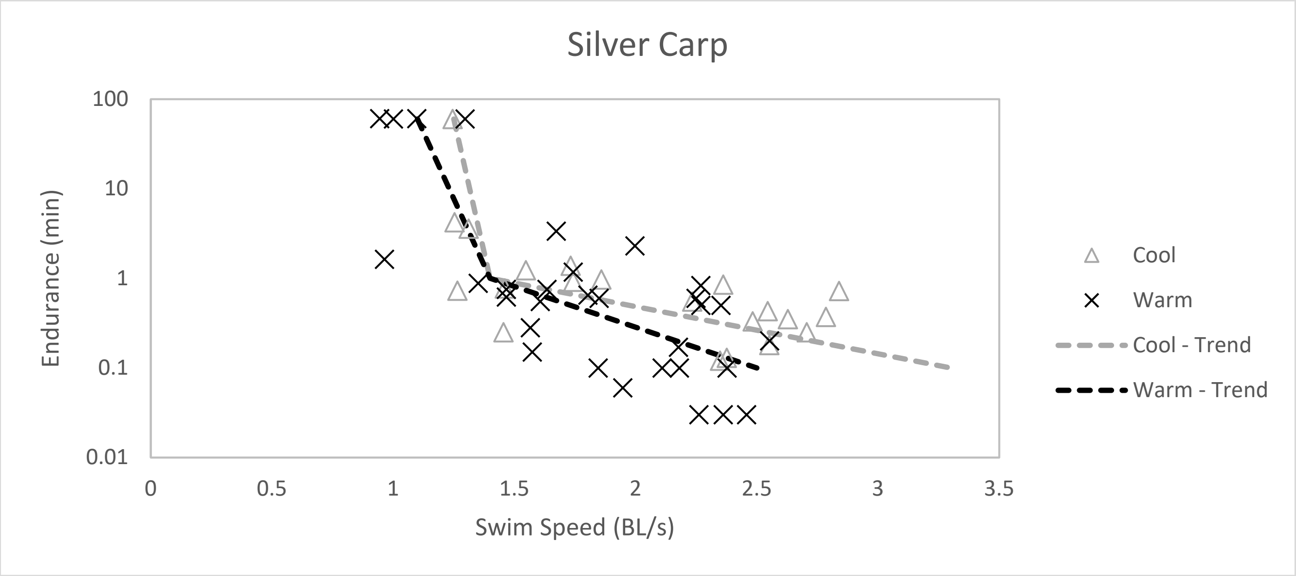


Figure 2.2. Time-to-fatigue curve for Silver carp at cool (10°C) and warm (25°C) water temperatures.

Final Report Summary:

All swimming performance tests and data analysis are now complete. The outcome was published with Dr. Hoover as first author to the *Journal of Applied Ichthyology* in 2016. Some of the key findings are that bigheaded carps are rather "average" swimmers, with silver carp being better than bighead carp, and size being important. Data are now being used in our agent-based models. Swimming performance was quantified for adult Silver and Bighead carp, 535-1040 mm total length, at unsustained swimming speeds (76-244 cm/s), corresponding to fatigue times less than 10 min. Finalized time-to-fatigue curves have been generated (Figure 2-3 and 2-4), with all non-performers (fish that did not orient to flow) and fish that did not fatigue (i.e. did not reach unsustained swimming speeds) were excluded from analyses. Analysis of swim data revealed log-linear models best described the relative swim speed to fatigue relationship for both species. The relationship between swimming speed and time follows

$$T = e^{a+bU_s}$$

where *T* is the endurance time, U_s is the swimming speed, and *a* and *b* are parameters fit from experimental data (Table 1).

To evaluate influence of fish size on data, swim speed (relative to body length) data for individuals were plotted against total length, along with data for juvenile and subadults previously documented (Hoover et al., 2012). We found that relative swim speeds of both species decreased with increasing total length (Figure 2-5). Adult Silver carp also exhibited higher relative swim speeds than adult Bighead carp. Dr. Jan Hoover submitted a final data report in January 2016. The finalized data can now be used in conjunction with the agent based fish passage model as described in Activity #1.

Table 1. Swimming performance characteristics for adult Silver and Bighead carp

Species	$U_{sustained}$ (BL/s)	a (mean± σ_a)	b (mean± σ_b)
Silver carp	1.25	1.92±0.65	-1.02±0.33
Bighead carp	1.00	5.52±0.73	-2.98±0.41

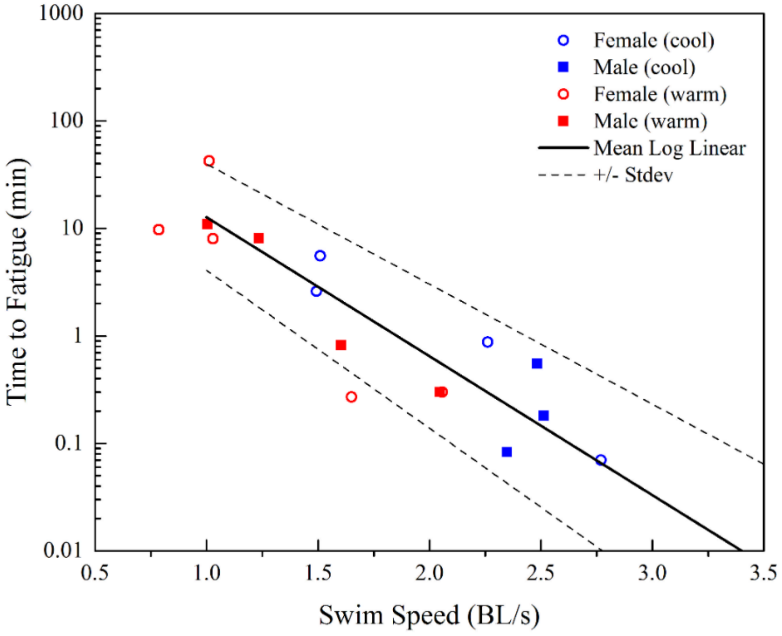


Figure 2-3. Log-linear model for Bighead carp (N=17) swimming performance. Boundaries on model are means ± S.D. Individual data points are coded to indicate water temperature (blue for cool water [10℃], red for warm water [25℃]) and sex (○ for female, ■ for male).

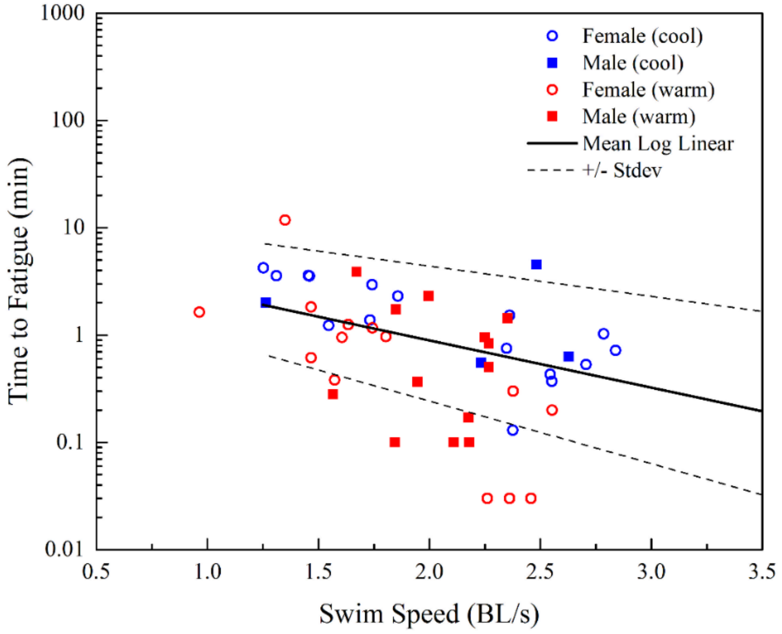


Figure 2-4. Log-linear model for Silver carp (N=43) swimming performance. Boundaries on model are means ± S.D. Individual data points are coded to indicate water temperature (blue for cool water [10℃], red for warm water [25℃]) and sex (○ for female, ■ for male).

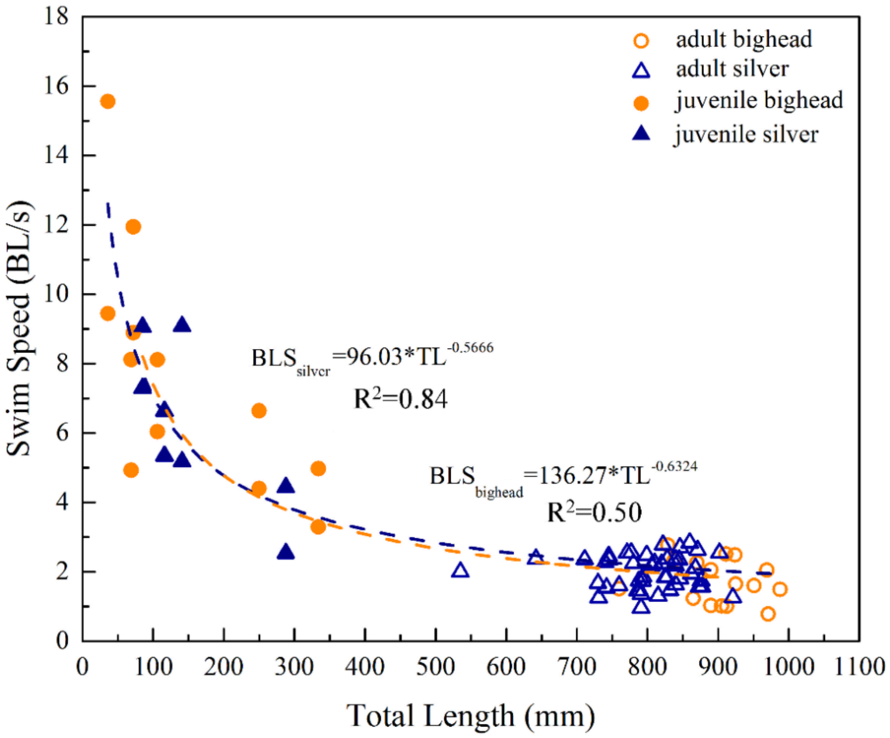


Figure 2-5. Relationship of swim speed to total length across juvenile and sub-adult (Hoover et al., 2012) and adult Silver (N=43) and Bighead carp (N=17). The equation and correlation of least squares for each line are provided.

ACTIVITY 3: Test and Develop New Accoustical Deterrent Systems for Locks that Deter Carp and Have Minimal Effects on Native Fishes.

Description: Lock chambers present a potential way for Bigheaded carps to pass upstream, irrespective of gate function. Presently, the MN DNR is funding experiments on possible low voltage electrical fields (‘sweeping’) that might be placed into lock chambers to serve this purpose but these systems are experimental, extremely expensive (up to 8 million dollars per chamber), and not guaranteed to be approved for use by the USACE because of possible safety issues. An alternative approach would be to employ sound (acoustic) deterrents, but we do not yet know which acoustic technologies might be most effective or how to deploy them. Sound deterrents have special promise because carps are ‘hearing specialists’; i.e. they have physiological specializations that make them uniquely sensitive to sound, and sound sources are safe (to humans and fish), relatively easy to mount, and inexpensive (costs are in the tens of thousands of dollars versus millions). We have been working with acoustical deterrents (ex. bubble curtains) for several years as have several other research groups. Three technologies have special promise: High-frequency underwater transducers (specialized underwater speakers,[these will also be installed at Lock and Dam #8]); ‘hydro-’ or ‘water-’ guns (implosive sound production devices used in oceanic seismic exploration) which produce pulsed acoustic waves; and ’boomer plates’ (another oceanic seismic exploration device) which produce pulsed low frequency acoustic waves, will be considered as ways to exclude fish from the lock chambers without negatively impacting lock structures or navigation. This activity will have several steps and have both laboratory and field components. Laboratory studies will evaluate the use of sound as a deterrent and allow us to develop it in ways that are not possible in the field because of logistical issues (ex. Bigheaded carps cannot be released and Lake Sturgeon are difficult to catch). Lab studies will also examine whether accoustical deterents might also repel Lake sturgeon, a low performance native fish of special interest and Brown trout, a high performance fish in lab arenas (these data will match up with Activity #1, see above). This work would take place in the winter and spring. Field work would take place in the summer in a decommissioned lock. In the first step of the field work , we will conduct pilot tests in a lock in 2014 to determine the best way to monitor fish (Common carp) near these technologies and pick one (or two) for formal testing in 2015. Underwater transducers will be initially tested in 2014 because they do not require special expertise and they will already be in placed in Lock and Dam #8. We will work with Dr. Jackson Gross from the research arm of Smith-Root Inc. (developer of water-gun and boomer plate concept, Vancouver, WA) at this time to identify technologies to be tested in 2015. As a second step in 2015, intensive study of at least one deterrent system will take place in a lock. All work will be conducted in a decommissioned auxiliary lock (Lock and Dam #1 [the 'Ford Dam'] in St. Paul) which the USACE has made available for our exclusive use and is providing assistance. Common carp will be used as a surrogate for Bigheaded carps because their hearing abilities and behaviors are seemingly identical to Bigheaded carps and they are already present in the river. The MN DNR will provide one part-time technician with a boat to capture carp. Advanced Telemetry Systems (ATS, Isanti, MN) will also be our partner and will provide expertise and if needed, fish tracking equipment gratis. Although the precise nature of the tracking gear and experiments has yet be determined (pilot experiments and the initial report in 2014 will accomplish this), it will involve capturing, tagging and then placing dozens of tagged adult common carp into the decommissioned lock chamber where their distribution and behavior will be monitored while acoustic devices are tested.

Summary Budget Information for Activity 3:	**ENRTF Budget:**	**$434,924**
	Amount Spent:	**$400,934**
	Balance:	**$33,988**

Activity Completion Date:

Outcome	**Completion Date**
1a. *Pilot tests in a lock and evaluation of a variety of acoustical technologies including transducers and a report /decision on the most promising one(s) (Field).* **1b**. *Understand if native Lake sturgeon are repelled by sound in the same manner as carps (lab)*	February, 2015
2. *Testing and documentation of effectiveness of at least one technology (likely water-gun) to repel carp within lock chamber #1 (Field).*	August, 2015
3a. *Testing and documentation of effectiveness of another promising technology (likely boomer plates) to repel carp from lock chamber #1 (Field)* **3b**. *Understand if Brown trout are repelled by sound in the same manner as carps (lab)*	February, 2016
4. *Report on the best technology to repel and exclude carp which should have minimal effects on native fish provided to USACE*	August, 2016
5. Testing different complex sounds and identifying the best one for carp and then identifying the frequency range(s) that is most important for at least one of these sounds	February 2017
6. Testing different temporal patterns of at least one type of complex sound on carp at optimal frequency ranges to identity the most promising set of combinations.	June 2017

Activity Status as of 2/28/2015:

1a. *Pilot tests in a lock and evaluation of a variety of acoustical technologies including transducers and a report /decision on the most promising one(s) (Field).*

In 2014 we successfully established a field test site, support system for the site, and an experimental design that will allow us to conduct experiments in 2015 and 2016. Briefly, we succeeded in establishing a rental agreement with US Army Corps of Engineers (USACE) to use the auxiliary lock in Lock and Dam #1 (St. Paul) for at least the next two years for our experiments on deterrents. The USACE have granted us ready access for the cost of the electricity alone. We have also established a collaboration with Advanced Telemetry Systems (ATS) in Isanti, MN and they are generously lending some of their two-dimensional tracking equipment to use in this auxiliary lock as well as engineer time free of charge. The Minnesota Department of Natural Resources (DNR) has also helped us catch and tag experimental fish (common carp) at the test site in 2014 and while they unfortunately will be unable to help us in 2015 due to lack of personnel they are going to provide us with the training and equipment to catch the test fish we will need. Because we originally had anticipated contracting with the DNR for this service, an amendment and re-budget will eventually be needed to reorganize our effort and costs. We also contracted with Smith Root Inc. (SRI) for expert advice on deterrents. Dr. Gross with SRI visited us and wrote a technical report on whether and how hydroguns (water-guns) and/or boomer plates (percussive sound sources that operate at very high amplitudes (190-210 dB but which cannot be tuned) could be tested in auxiliary lock #1 and what their ultimate promise in Minnesota might be. SRI is the leading developer of these technologies and have at least 5 years of experience with them. Unfortunately, while insightful, the SRI report did not describe either clear or unique promise (either conceptual or field data) for either technology at the invasion front situation in Minnesota where native fish are of high concern. Both hydrogun and boomer plate technologies are extremely expensive (seemingly hundreds of thousands of dollars would be required for purchase and installation of a single unit), and hydroguns would have high maintenance demands, safety issues and would threaten to injure native fishes. Further, hydroguns are already being extensively tested by the US Geological Survey (USGS) in Illinois and have seemingly not shown special promise to date as silver carp swim through them routinely while they kill gizzard shad (personal communications with USGS). Alternatively, while SRI described data in their report that boomer plates are easier and safer to mount, the frequency of sounds they produce can seemingly be replicated by our underwater speakers at much lower cost and ease (albeit at slightly lower amplitude but we have found we do not and cannot run the speaker at peak volume anyway). Consequently, we have decided not to test either hydroguns or boomer plates in the summer of 2015 but instead focus on conducting various tests with our underwater speakers to both mimic boomer plates sounds and motor boat sounds which lab experiments already show to have promise (see below). If time permits we will also test lights in 2015 and we are in talks with Fish Guidance Systems (UK) about a possible collaboration to test a bio-acoustic fish fence (BAFF) and/or sound projector arrays (SPA), perhaps in 2016. Other technologies are still being evaluated (lights alone, possible bubble curtain). When a final decision is made(after this year's field tests) about the most promising alternative carp deterrence technology, an amendment and re-budgeting of the project will be proposed (likely August 2015).

In addition to establishing how we will use the auxiliary lock facility in 2015, we ran several pilot experiments in the auxiliary lock in 2014 that have established specific experimental protocols. Briefly, we have found that we can capture adult Common carp in the area using boat electrofishing. We have also discovered that we can easily and safely tag carp with small JSAT acoustical tags (ATS) and then move them into the auxiliary lock where we hold them using a 60 foot net that we can insert into a groove already found in the lock wall. This net can be lowered to release fish but the technique is complicated because lock water depth is too deep (9-12 feet) to permit electrofishing in the chamber; however by using multiple groups of acoustically tagged fish with individual codes, we can solve this problem by adding new test fish into the auxiliary lock to perform replicate experiments. We have also found that trapped test fish thrive in the lock chamber, but if kept in smaller cage systems outside the chamber they get sick (so we will catch and place test fish into the chamber as needed). Further, working with ATS engineers we have been able to develop a two-dimensional tracking array using 4 hydrophones that should be able to resolve the locations of tagged carp within 5 m (work continues on coding). In November 2014, we conducted a dry run of proposed 2015 experiments in which common carp (n=7) were surgically implanted with an acoustic tag and released into the auxiliary lock chamber. Common carp moved through the length of the lock chamber, and individual fish locations were detected approximately every 20 seconds. Lastly, we were able to temporarily mount one Lubell underwater speaker in a lock chamber at Lock and Dam #2 in Hastings, MN (ice buildup in the auxiliary lock precluded this test at Lock and Dam #1, but Lock #2 is nearly identical to Lock #1) and test the sound field it produced. The transducer played a complex sound (derived from a recording of a boat motor) between 600-3000 Hz with a peak sound pressure level of 190 dB and a spectral level of 160 dB at 600 Hz. It created a sharp sound pressure gradient that extends 20 m, an ideal range for testing in the auxiliary chamber (~150 m long) as fish will have sufficient room to respond to sound and seek quieter habitat. Field studies for 2015 are now planned to examine common carp movement in response to an unaltered continuous boat motor sound, a filtered continuous boat motor sound (600-3000 Hz), and a variable sound source (continuous filtered boat motor sound supplemented with a burst of high intensity sound at variable intervals) as well as boomer plate sound. Responses of at least one native fish will also be tested to the sound sources. Fish will be tested in groups on a daily basis with 4-5 naïve fish being added about twice a week. The planned tests appear doable.

1b. *Understand if native Lake Sturgeon are repelled by sound in the same manner as carps (lab)*

We have also completed initial trials of sound deterrents in the laboratory, and results suggest that native lake sturgeon are not repelled by a boat motor sound that deters bigheaded and common carps. These studies are ongoing and are being conducted in a square plastic enclosure (1.8 m side, 30 cm water depth) with four transducers placed at the center of each wall. Groups of 3 fish from one of 5 species (silver carp, bighead carp, common carp, lake sturgeon, or brown trout) are placed in the square enclosure and fish movement is monitored using an overhead video camera. Avoidance of the boat motor sound has been quantified as a decrease in the amount of time fish spent within 30 cm (the distance at which the greatest change in sound pressure occurs) of an underwater transducer while sound was played (i.e., treatment) or not (i.e., control). Silver carp, Bighead carp, and Common carp decreased time spent within 30 cm of the transducer from approximately 9% during controls down to 2% when sound was played (Figure 3.1). In comparison, lake sturgeon spent 8.2% of the time within 30 cm of the transducer during controls while spending 7.9% when sound was played (Figure 3.1). Although the sound used in these trials contained frequencies within the lake sturgeon hearing range (< 600 Hz), the sturgeon did not exhibit any tendency to avoid the sound source. Laboratory testing has also been completed with brown trout (outcome 3b), however analysis of this data is ongoing and expected to be completed by August. Due to renovations planned for the aquaculture facility starting in mid-April through December 2015, laboratory trials with brown trout are now being conducted to try and complete this work sooner than proposed. Further laboratory testing is also now underway to understand whether modifying the sound frequency range of this signal will increase the species-specificity, as carps have greater sensitivity to higher frequencies (600-3000 Hz) compared to many native non-cyprinid fishes. We expect these tests to be completed this spring, so we can use this data to increase the efficiency of our field-scale experiments in the auxiliary lock chamber.

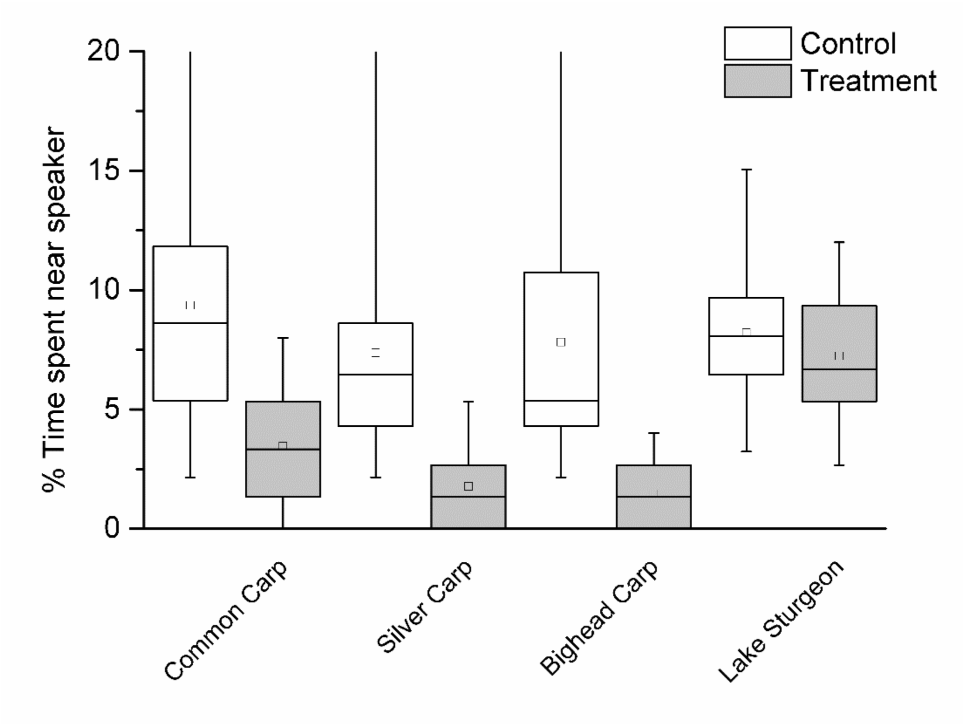


Figure 3.1. Percent of time Common carp, Silver carp, Bighead carp, and Lake sturgeon spent within 30 cm of a speaker playing motorboat sounds while ON (treatment) and OFF (Control). All carp species exhibit a significant decrease in time spent near the speaker while ON (P<0.05).

Activity Status as of 9/30/2015:

Several tests of the effectiveness of an unaltered continuous boat motor sound to repel common carp within a lock chamber have been completed with positive results and more are now underway. An unaltered boat motor sound was chosen for testing this year based on laboratory results using this sound which showed it to be much more effective than a truncated sound (see previous status report). Hydroguns were not tested because they were deemed to not be promising based on the Smith Root report we commissioned earlier and results of other research groups. Work in the lock has been delayed by numerous technical issues which have now largely been resolved. Briefly, exptertiment setup started in June 2015 in the auxillary lock of Lock&Dam #1 , following a period of high water. The lock chamber was initially fitted with two blocking fish nets which were placed at either end of the chamber to create a 95 m long x 17 m wide x 3 m deep experimental test chamber. Unfortunately,river otters (which were not present last year) chewed through this netting three times (causing 3 week-long delays) but the situation has now been resolved using a custom built chicken wire screen we have inserted in its place(we ask for funds to install a gate next year). Placement of the netting/chicken wire screen was also greatly complicated by unexpected (unknown) step on the lock floor 92 more weeks lost). Further delays came when the new speakers broke (they were eventually fixed for free under guarantee, another week) and the DNR was unable to provide us with help for electrofishing and then the used electrofishing boat they sold us (at very noiminal cost) broke (another week; we now ask for funds for repairs and more help in our rebudget). Additonal challenges came when more echoing was encountered in the lock chamber than expected and the live two-dimensional tracking system did not work as expected. This was remediated gratis by Advanced Telemetry Systems (ATS) Inc. which supplied both free engineering help and lent us a set of 6 accoustic receivers (we now ask for funds to buy them). The current tracking system operates well and with greater than 80% accuracy. An underwater speaker (LL-1424, Lubell Labs), matching those installed at Lock and Dam #8, is also now located at either end of the blocking wire nets. Speakers have been mounted on floats and produce a peak sound pressure level of 180 dB (ref. 1 μPa) at 1 meter from the speaker (confirmed by sound mapping ; Figure 3.2). Contour maps of the sound pressure level throughout the lock chamber show a sharp sound pressure gradient that extends 40m away from the speaker . The experimental set-up was finally completed mid August 2015, and experiments have been ongoing ever since. These have included three trials using common carp (one still not analyzed) along with one set of experiment s with lake sturgeon which the USFWS generously captured for us. Meanwhile, we have completed laboratory trials with two types of sound deterrents, the unfiltered boat motor sound and a restricted (>1000Hz) frequency version of the boat motor sound, on 3 species of carp (common, silver, and bighead carp) and 2 non-cyprinids (lake sturgeon and brown trout). Results from these studies will be presented in the February 2016 status report, as described in the the work plan. Clark Denis, the technican, has decided to assume responsibility of this project and make it a Ph.D. Here we focus (as planned) on describing results from the field tests in the auxiliary lock.

Experiments in the auxillary lock began August 25th and we report here intial unprocessed results from three complete experiments. Data are still being analzed but are promising. Adult common carp have been captured using boat electrofishing in lower Pool 2 of the Mississippi River while lake sturgeon have been obtained using gill nets on the St. Croix near Stillwater. All captured fish have been implanted with JSATS acoustic transmitters (ATS) and placed into the auxiliary lock as groups of 5. After acclimating overnight, we have then played a complex sound derived from an outboard boat motor (the same sound that was also used in the laboratory). Fish movement and position has then been monitored every 15- sec for a 45-min period without sound (control) followed by a 45 min period with sound (test). Two paired trials (control and test periods) have been conducted each day until we have 7 replicates. To date, we have successfully completed two experiments with common carp and one with lake sturgeon. All trials show that common carp spend nearly 50% less time near the speaker when the complex sound is played and that this response lasts about 5-10 minutes. This should be long enough to divert fish in the river from entering the lock (Figure 3.2A,B). Close inspection of the data shows that once the sound is played, carp generally swim to the opposite end of the chamber. In contrast, lake sturgeon (a native fish of special interest) have not shown any apparent avoidance to the complex sound (Figure 3.2C). Additional groups of common carp will be tested to fully quantify the avoidance response. Work will continue as long as weather permits in 2015. If possible, additional field studies are planned to examine common carp movement in response to boomer plate sounds, an impulsive sound source. These experiments should be completed by November 2015 and analyzed by February 2016. Unfortunately due to the delayed start-up, additional sounds [filtered continuous boat motor sound, variable sound source (continuous sound supplemented with a burst of high intensity sound at variable intervals)] and additional deterrent systems (strobe lights) can not be tested during the 2015 field season. However, we plan to test the variable sound source, as well as an additional deterrent system (a bubble curtain) in the laboratory. Very likely these laboratory tests will be expanded to include additional types of sounds because of their promise and the fact that laboratory studies are much easier to conduct than field studies. We are proposing to conduct much of this work in collaboration with Fish Guidance Ltd., an English company that specializes in air curtain systems . Further details about these plans will be aviailable in our next update and may require another amendment depending on how well final costs match our plans.

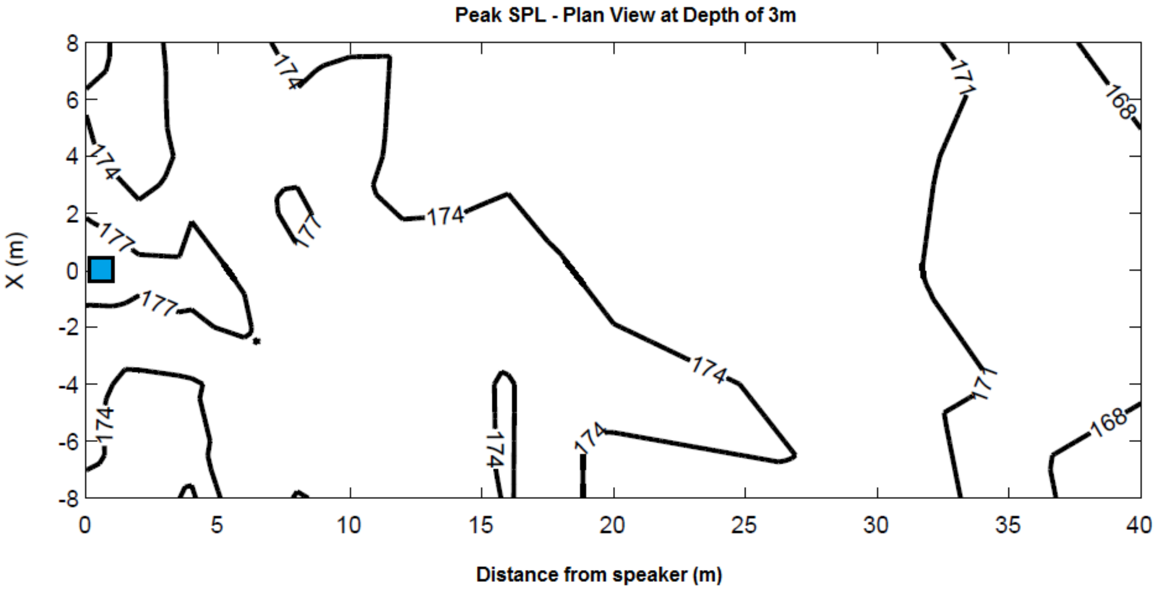


Figure 3.2. Contour plot of the peak sound pressure level (SPL dB ref 1μPa) produced by one Lubell Labs speaker (☐), cross-section at a depth of 3 m from the water surface in the auxiliary lock.

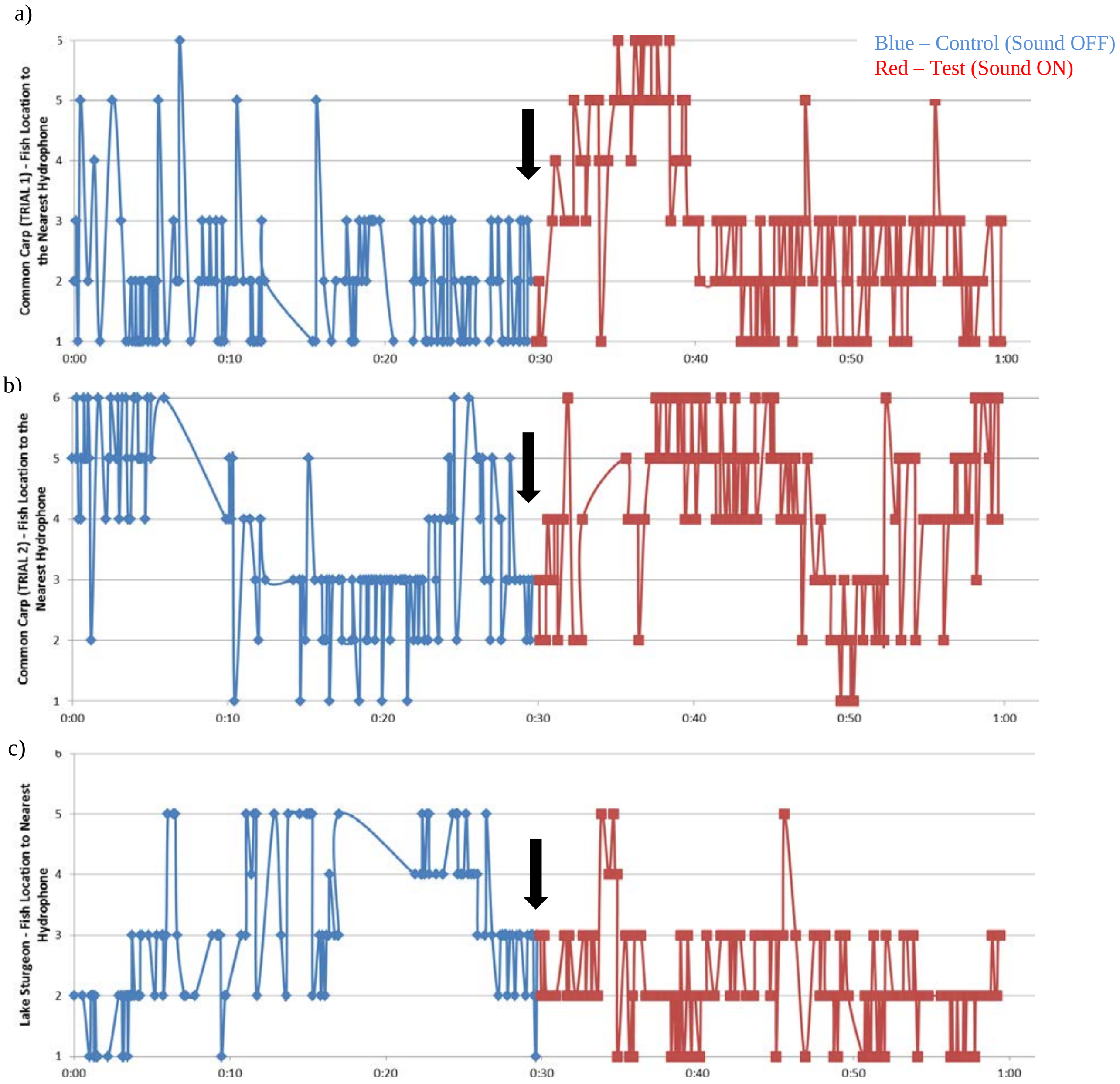


Figure 3.3. Raw data of the movement of individual common carp during Trial Week 1 (a) and Trial Week 2 (b) and lake sturgeon (c) for a 30 min control period (Sound OFF; blue dots) and 30 min test period (Sound ON; red dots). The black arrow denotes the time that the underwater speaker was activated near hydrophone 1. Fish location based on hydrophone location as a reference to speaker location is as follows: H1 (0-5m), H2 (5-20m), H3 (20-47.5m), H4 (47.5-75m), H5 (75-90m), and H6 (90-95m).

Activity Status as of 2/29/2016:

Overall, work is going well inspite of many challenges. Here we report on: 3-i) Final analysis of our field and lab data from the past spring and summer; 3a)Testing and documentation of effectiveness of another promising technology (likely boomer plates); 3b) test of whether Brown trout are repelled by sound in the same manner as carps; and 3c) Perspectives on future work for this summer.

3') Final analysis of our field and lab data from the past summer:

We completed analysis of the summer 2015 field trials that had examined the responses of common carp and lake sturgeon to an unproccssed boat motor sound (10-10,000 Hz). These experiments clearly showed that we could repel carp for at least 15 min on 2-3 occassions using an outboard motor sound and that lake sturgeon were not affected. Trials were conducted in the auxiliary lock chamber (Lock and Dam #1, St. Paul) from August 25th – October 29th 2015 (late because of many technical challenges –see last August report). During this time period, we were able to conduct several replicated studies with groups of 5 common carp (N=6 groups). We were also able to test with one group of 8 lake sturgeon that were captured on the St. Croix River. Briefly, we tagged groups of common carp or lake sturgeon from the Mississippi River and placed them into the auxiliary lock chamber. Fish were allowed 24 hours to acclimate to the lock chamber. Fish movement and position were monitored using a fish tracking system provided by Advanced Telemetry Systems, which allowed us to determine fish location (within 5 m) relative to the underwater speakers placed at the ends of the lock chamber. Fish movement was monitored for at least 45 min prior to the activation of the speaker, which was playing the unfiltered boat motor sound (10-10,000 Hz) which was shown to be effective in eliciting avoidance in carps in a laboratory setting. The speaker was activated when the majority (≥ 3) fish were within 20m of the speaker for at least 5 minutes. The speaker was then allowed to play continuously for 45 min. This procedure was repeated twice per day (10AM and 3PM) over a 4 day period resulting in a total of 8 trials per group of fish. After the 4 day testing period, the fish were allowed to escape the lock chamber and a new, naïve group of fish were added the following week. Results show that common carp were repelled approximately 40 meters by the boat motor sound during the first few trials (1-3) over a 15 min period; however, this avoidance response diminished following multiple playbacks (Figure 3-4). Figure 3-4 (a,b,c) and Figure 3-5 (a) shows the average distance away from the activated speaker for specific groups of common carp. While only 4 groups of common carp data are shown, the other two groups had a similar response to the unfiltered boat motor sound (i.e., 40 m avoidance for first 1-2 trials then loss of avoidance response in subsequent trials). Lake sturgeon did not exhibit any change in their movement following activation of the boat motor sound [Figure 3-5], similar ot earlier lab work.. Overall, field tests for the unfiltered boat motor sound showed that this sound can repel common carp although responses habituated. Because this field work was very time consuming, and merely confirmed laboratory work, we propose on laboratory work this upcoming summer that addresses habituation using different sounds (see section 3C below). Notably, the new laboratory facility should be available by April. Next year we will likely propose to move back to the field.

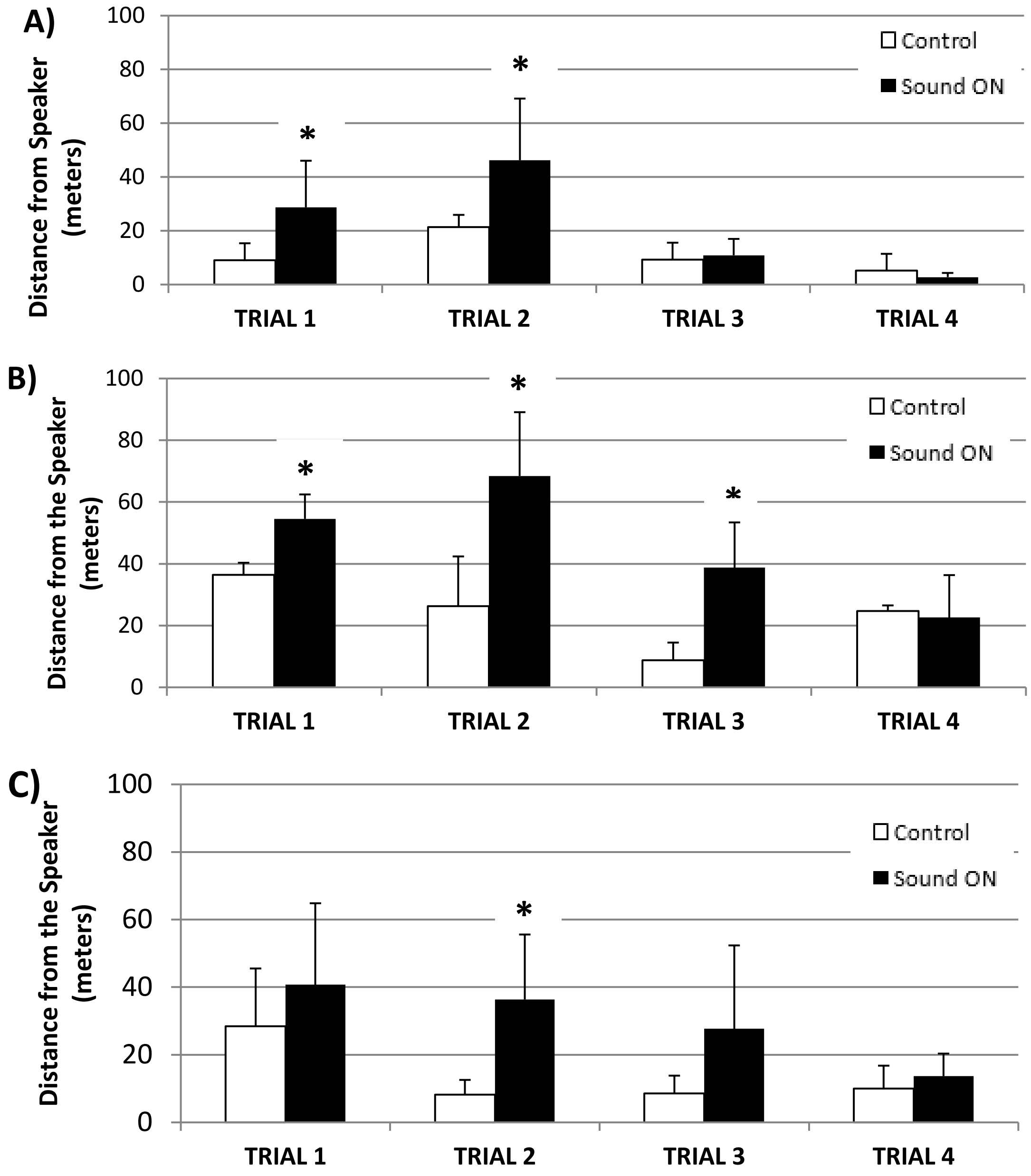


Figure 3-4: Average distance of 5 common carp in relation to the activated speaker when turned ON (Sound ON) or OFF (Control). The three panels (A,B,C) show data collected for a specific group of common carp (Groups 1-3) for the first 4 times the speaker was activated (Trials 1-4). The white bars depict the average distance of a group of fish relative to the speaker over a 15 min period prior to activation of the speaker (Sound OFF; Control). The black bars depict the average distance of a group of fish relative to the speaker over a 15 min period beginning when the speaker was turned ON (Sound ON). Asterisks denote statistically significant increase in the distance that a group of fish was from the activated speaker.

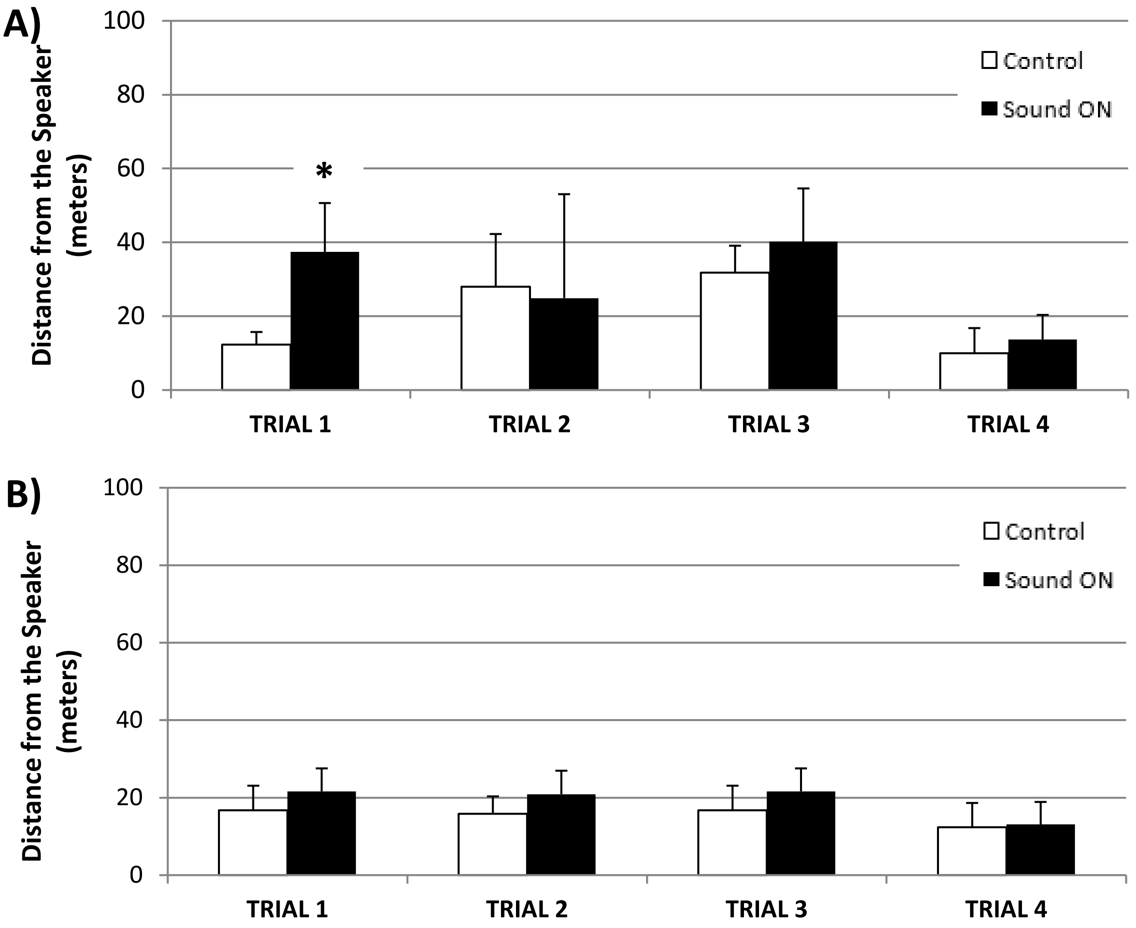


Figure 3-5: Average distance of 5 common carp (A) and 8 lake sturgeon (B) in relation to the activated speaker when turned ON (Sound ON) or OFF (Control) for the first 4 times the speaker was activated (Trials 1-4). Common carp data depicted in (A) is taken from the 4th group of carp that were tested. The white bars depict the average distance of a group of fish relative to the speaker over a 15 min period prior to activation of the speaker (Sound OFF; Control). The black bars depict the average distance of a group of fish relative to the speaker over a 15 min period beginning when the speaker was turned ON (Sound ON). Asterisks denote statistically significant increase in the distance that a group of fish was from the activated speaker.

In addition to finishing field tests, we finished analyzing the lab data cthat we had ollected in the early summer of 2015 which sought to determine if playing only that portion of the outboard motor sound signal that fell between 1000-10,000hz might be as repellent as the entire signal to carp but have diminished effects on nonhearing specialsists scuh as trout that have little hearing sensitivity in this range. We discovered that the carp[species were no longer sensitive to this restricted frequency range although startle responses in brown trout were reduced (Figure 3-6).

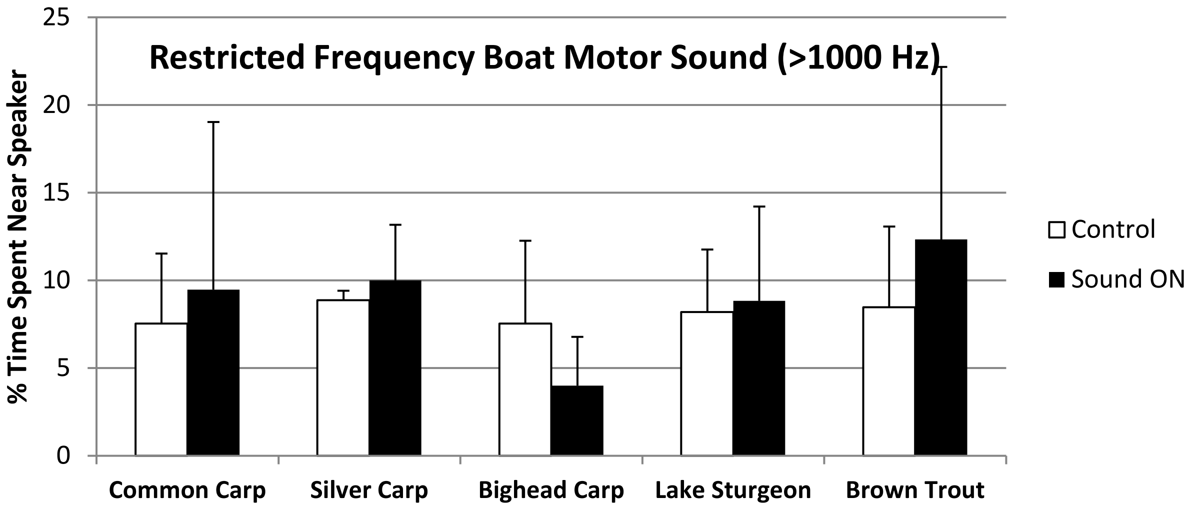


Figure 3-6: Upated figure from August progress report showing Percent time common carp, silver carp, bighead carp, lake sturgeon and brown trout spent within 30 cm of a speaker playing a restricted frequency boat motor sound (>1000 Hz) while OFF (Control) and ON (Sound ON). All species showed no difference in the amount of time spent near the speaker when activated or not.

3a. Testing and documentation of effectiveness of another promising technology (likely boomer plates) to repel carp from lock chamber #1 (Field).

Using a speaker, we succeeded in simulating the boomer plate sound in the auxialliry lock in late November. A spectrogram of the sound and a plot describing signal intensity is shown below (Figure 3-7). However, playing this sound proved to technically challenging (we blew one speaker) and by the time the speaker was operational, it as unfortunately too late (cold) to test common carp. Althought we can now create this sound, we nevertheless believe that work with this sound should not be continued in favor of other options because: 1) our tests of restricted sound frequencies of outboard motor sound (Figure 3-6) have already demonstrated that they are less effective than more complex broad-band signals (the boomer plate signal is restricted to low bandwiths) ;2) work in the field using another impulsive sound source, hydroguns, has just been published (Romine et al., 2015 NAJFM) and shown it to have little promise; 3) these sounds are technically difficult to produce; and 4) more promising options are now evident (see section 3c below).

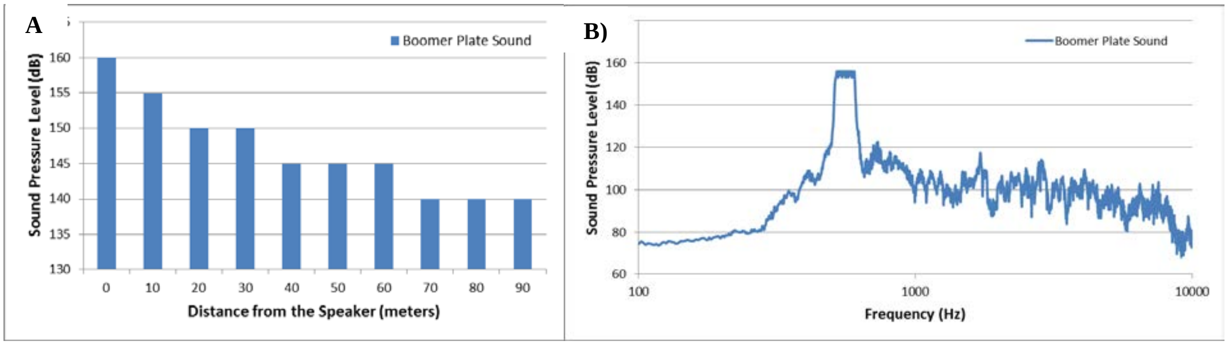


Figure 3-7: Sound measurements taken at the auxiliary lock chamber for the impulsive boomer plate sound. Sound pressure level for the boomer plate sound (peak at 600 Hz) taken at 10 meter intervals along the center of

the lock chamber (Panel A). Spectrogram of the boomer plate sound taken at 2m from the activated speaker (Panel B).

3b. Understand if Brown trout are repelled by sound in the same manner as carps (lab);

The results of laboratory studies performed during Spring 2015 (prior to this report and the demolition of the laboratory aquatic facility) are now complete and include brown trout. Brown trout were not repelled by the unprocesseded outboard motor sound but often responded with freezing (Fig. 3-8). This response disappeared when this signal was filtered (see Section 3-I; Figure 3-6).

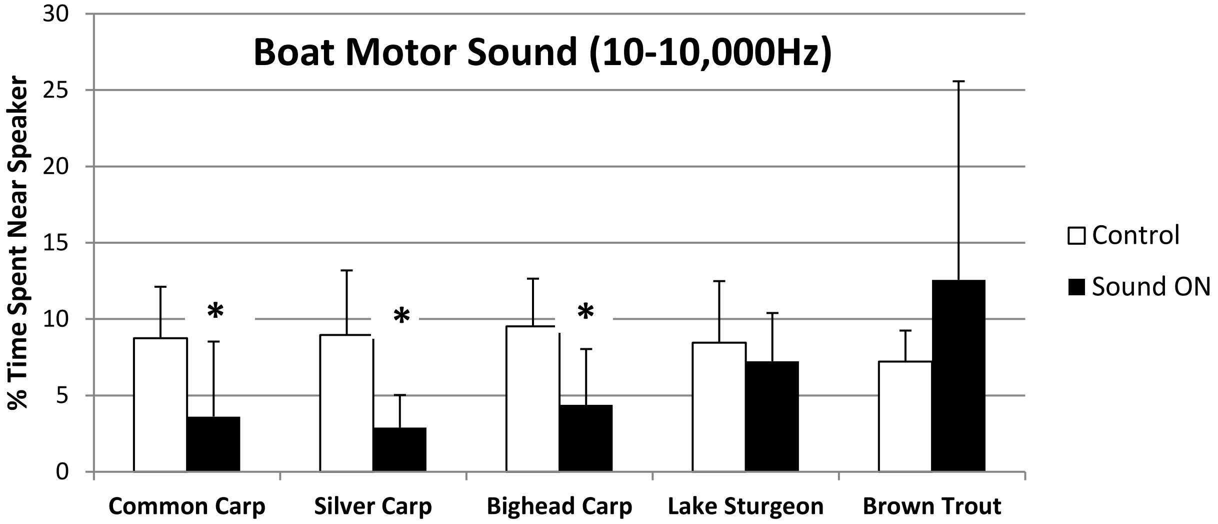


Figure 3-8: Update of Figure 3-1. Percent of time common carp, silver carp, bighead carp, lake sturgeon and brown trout spent within 30 cm of a speaker playing the unfiltered boat motor sound while OFF (Control) and ON (Sound ON). All carp species display significant decreases in the amount of time spent near the speaker with ON (P < 0.05). Lake sturgeon and brown trout did not actively avoid the area with 30 cm of an activated speaker.

3c) Perspectives on work for this summer

Our results to date (summarized above) clearly demonstrate that common carp, bighead, and silver carp are all equally and strongly repelled by complex outboard motor sounds played by speakers in the laboratory while sturgeon and trout are not. Other, less complex sounds have less activity but repeated exposure do lead to habituation. Air curtains have also proven to be effective deterrents for carp. Additionally, in all cases, field results have closely mimicked laboratory results. Because field work is also much more expensive, difficult and slower to perform, we will therefore move this summer's work to the laboratory where we will focus on the hypothesis that complex sounds are likely to be more aversive and resistant to habituation that simpler sounds. We will test increasing the spectrum of frequencies found in sound signals, their amplitiude variation, and finally their temporal character/ complexity. We would also test the hypothesis that air curtains can be combined with a sound source to create sharp sound gradient that will be especially effective at deterring carp. Work will focus on common carp which are much easier to study than bighead and silver carp but respond in similar fashions. This will accelerate progress so we can make recommendations. We will likely include technologies including the BAFF air curtains developed by Fish Guidance System Inc (U.K.) (as a contract approved in last ammendament) in this work, thereby taking advantage of their 20+ years of experience in this field. A field study to confirm findings will be attempted if time permits. The savings in funds and time should permit us to ask for an amendment and rebudget at the time of our next report to extend this work though June 2017 with proof-of concept tests that include silver and bighead carp and a field test. We nevertheless, should still be able to make initial recommendations for sound deterrent systems for possible implementation by August. We will proceed with this approach unless we hear otherwise.

Activity Status as of 8/31/2016:

This project has clearly demonstrated that sound can deter invasive carp both in the field and laboratory while having little effect on at least some native fishes. Deterrence rates approach 70% and it appears that a broad sound spectrum is required but we do not understand the frequencies or temporal patterning that might work best. Conversely, impulsive sounds produced by both air gun and boomer plate technologies seem to have little promise (see a recent published study by Romine et al. (2015) Responses of bighead carp and silver carp to repeated water gun operation in an enclosed shallow pond; North American Journal of Fisheries Management 35: 440-453.) Additonally, our work (Zielinski et al. in preparation) strongly suggest that sound gradients such as those produced by air curtains enhance deterrent effectiveness. Accordingly, we both proposed developing and implementing these systems at Lock and Dam #5 and strongly recommended to the MN DNR and USACE as well as the LCCMR that these options be pursued. Funding has not materialized but we have been advised by the LCCMR that we may seek an amendment to fund continued laboratory work as part of ENRTF2014 so that is proposed as part of the amendment to this activity, as described above, and then later (2017-2018) in ENRTF 2013. This research would employ a small-scale model sound deterrent system we have leased from Fish Guidance System Ltd (U.K). and which is finally operating in the labatory after a 6 month delay associated with construction. Outcomes to this workplan are amended accordingly.

Activity Status as of 2/31/2017:

We have now completed tests quantifying the avoidance response of common carp to three complex sounds in the laboratory. Result are very promising and work is now underway using bigheaded (invasive) carps and appears equally promising. We have examined three complex sounds: 1) an unmodified outboard boat motor sound (10 – 10,000 Hz); 2) a restricted-frequency boat motor sound (1000 – 10,000 Hz) (initial results reported 2/2017), and 3) a proprietary commercial signal provided by Fish Guidance Systems (FGS). Tests have been performed in a large circular flume with two underwater speakers placed at the center of each16m long straightaway section in the AIS research lab (Figure 3-9). Tests were conducted in complete darkness and fish movement was monitored using an overhead camera system and infrared lights. Trials started by adding 10 naive common carp into the flume and allowing 1 hour for these fish to acclimate to the testing arena. Background movement across each of the speaker systems was then measured during a 6 min control period when the sound deterrent system was off, and then during another 6 min exposure period when the sound system was on. Fish were then allowed 10 minutes to recover (i.e., return back to background movement rates) from this sound exposure. This control-exposure-recovery protocol was repeated a total of 8 times for each group of carp to assess if/how the avoidance response of the group changes over time (i.e habituation). Eight groups of 10 common carp were used for each complex sound signal examined. Avoidance to each sound treatment was defined as a decrease in passages across the speaker system during exposure periods (i.e., Sound on) compared to passage rates during the control periods (i.e., Sound off). Common carp exposed to the unfiltered outboard boat motor sound displayed a 10% reduction in passage rates during the first exposure and a 40-50% reduction in passage rates during all subsequent exposures 2-8 (Figure 3-10A). In contrast, Common carp exposed to the FGS Signal displayed over 80% reduction in passage rates for exposures 1-4 and a 60% reduction for exposures 5-8 (Figure 3-11B). These results clearly demonstrate that the FGS Signal is much more aversive to common carp than the outboard boat motor sound and is able to stop about 90% of all carp consistently. Several pilot studies using an air curtain with this sounds (experiments formally being planned for fall 2017 as part of a proposed amendment to ENRTF2013) show even high blockage rates above 95%. Laboratory trials are now examining bighead carp avoidance responses to the complex sound signals mentioned above. Preliminary results suggest that bighead carp are even more sensitive to sound than common carp with nearly 90% reduction in passage rates to the FGS Signal alone. Next, we will test this optimized FGS sound at a different temporal pattern as originally proposed and report by June with the project is scheduled to end.

FIGURE 3-9. Custom built circular flume (26m long x 3m wide) used for laboratory behavioral tests examining the avoidance response of carps to different aversive stimuli.

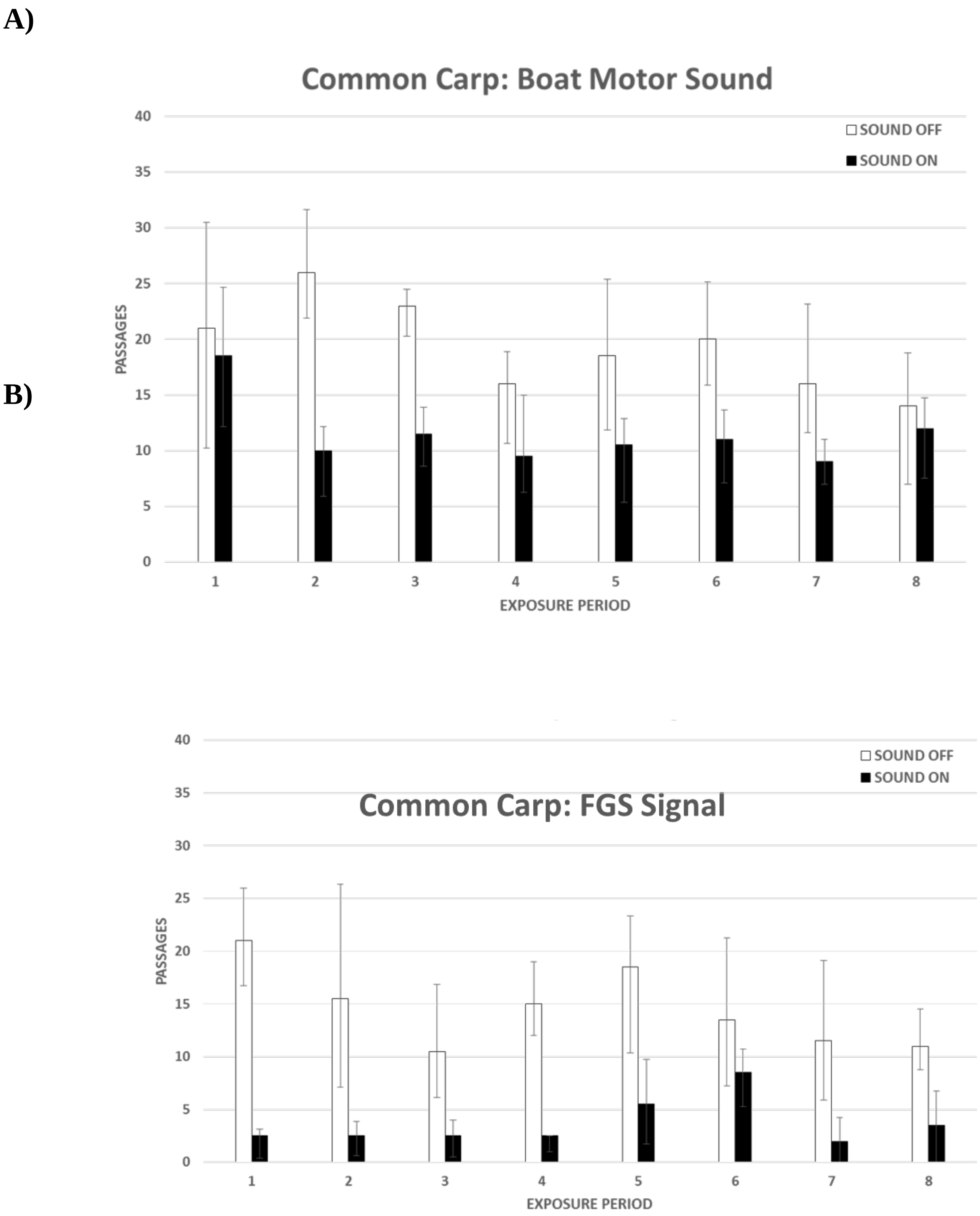


FIGURE 3-10. Passage rates during control periods (i.e., white bars) and exposure periods (i.e., black bars) for common carp over 8 exposure periods. Panel A shows results from common carp exposed to the unmodified Outboard Boat Motor Sound, while Panel B shows results from common carp exposed to the Fish Guidance System(FGS) Signal. N=8 Groups per complex sound treatment

Activity Status as of 6/30/2017:

We have completed laboratory tests quantifying the avoidance response of common carp and bighead carp to three complex sounds that differ in their temporal patterns. Results are very promising for carp and work using largemouth bass (a native fish) have now started ahead of schedule as part of ENRTF2013 Activity3) and suggest they are less impacted by sound than carps. Briefly, we hae now examined three complex sounds with different temporal patterns: 1) a continuous broadband outboard boat motor sound; 2) a sweeping proprietary commercial signal provided by Fish Guidance Systems (FGS) that is pulsed at a 2Hz rate (hereafter referred to as FGS Signal 1); and 3) a sweeping proprietary commercial signal provided by Fish Guidance Systems (FGS) that is pulsed at a 4Hz (hereafter referred to as FGS Signal 2]. Tests were performed in the large circular flume described in the previous update (see Figure 3-19) following the same protocol. Fish Guidance Ltd is a British company that has been working with sound for over 20 years and has developed their own sounds and technologies to broadcast them, and deployed them worldwide with considerable success.

Common carp exposed to the outboard boat motor sound displayed an approximate 10% reduction in passage rates during the first exposure and an approximate 40-50% reduction in passage rates during all subsequent exposures (#2-8) (Figure 3-11A). In contrast, common carp exposed to the FGS Signal 1 displayed over an 80% reduction in passage rates for exposures #1-4 and a 60% reduction for exposures #5-8 (Figure 3-11B). Similarly, common carp exposed to the FGS Signal 2 displayed approximately 75% reduction in passages rates over the eight exposure periods (Figure 3-11C). These results clearly demonstrate that the pulsed presentation of both FGS Signal 1 & 2 is much more aversive to common carp than the continuous presentation of the outboard boat motor sound and that this sound does not suffer loss of effectiveness over time. However, the specific rate of the pulsed signal does not seem to influence the overall avoidance response in common carp.

Bighead carp were more sensitive to sound than common carp, especially the FGS sounds. exposed to the outboard boat motor sound initially displayed an approximate 50% reduction in passage rates during the first two exposures; however this avoidance response to this sound increased to nearly 90% deterrence by the eighth exposure (Figure 3-12A). In contrast, bighead carp displayed over 90% reduction in passage rates over all eight exposures to FGS Signal 1 (Figure 3-12B). Similarly, bighead carp exposed to the FGS Signal 2 displayed approximately 80% reduction in passage rates over the eight exposure periods (Figure 3-12C). Similar to the results obtained for common carp, bighead carp were much more averse to acoustic signals with pulsed temporal presentations [i.e., FGS Signal 1, FGS Signal 2] than continuous temporal presentations [i.e., boat motor sound]. Interestingly, bighead carp appear to be more sensitive (i.e, more averse) to acoustic stimuli than the common carp that we tested. This difference in carp species sensitivity to sound has also been observed by Murchy et al. (2017) and Zielinski and Sorensen (*2017*); and also suggests that using common carp as a surrogate species in acoustic field trials will result in conservative findings. Preliminary tests of largemouth bass (a native fish) suggest they are much less sensitive to all sounds including the FGS sounds than bighead carp or common carps.

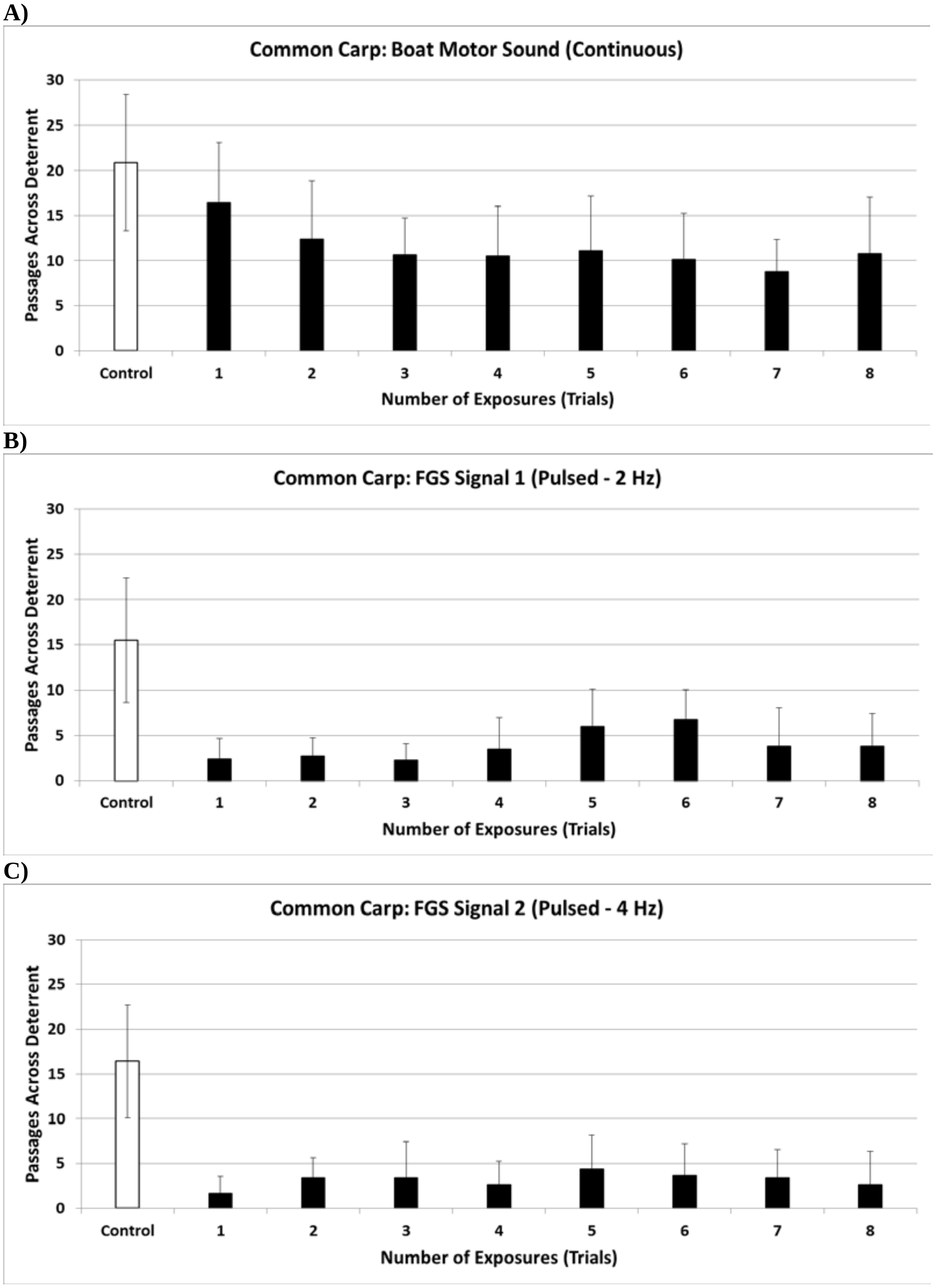


FIGURE 3-11. Passage rates during the typical pretest control period (i.e., white bar: average of all 8 pretest control periods) and each exposure periods (black bars: rates per individual exposure period) for common carp. Panel A shows results from common carp exposed to the Outboard Boat Motor Sound, Panel B shows results from common carp exposed to the Fish Guidance System (FGS) Signal #1, and Panel C shows results from common carp exposed to the FGS Signal #2. N=8 Groups per complex sound treatment.

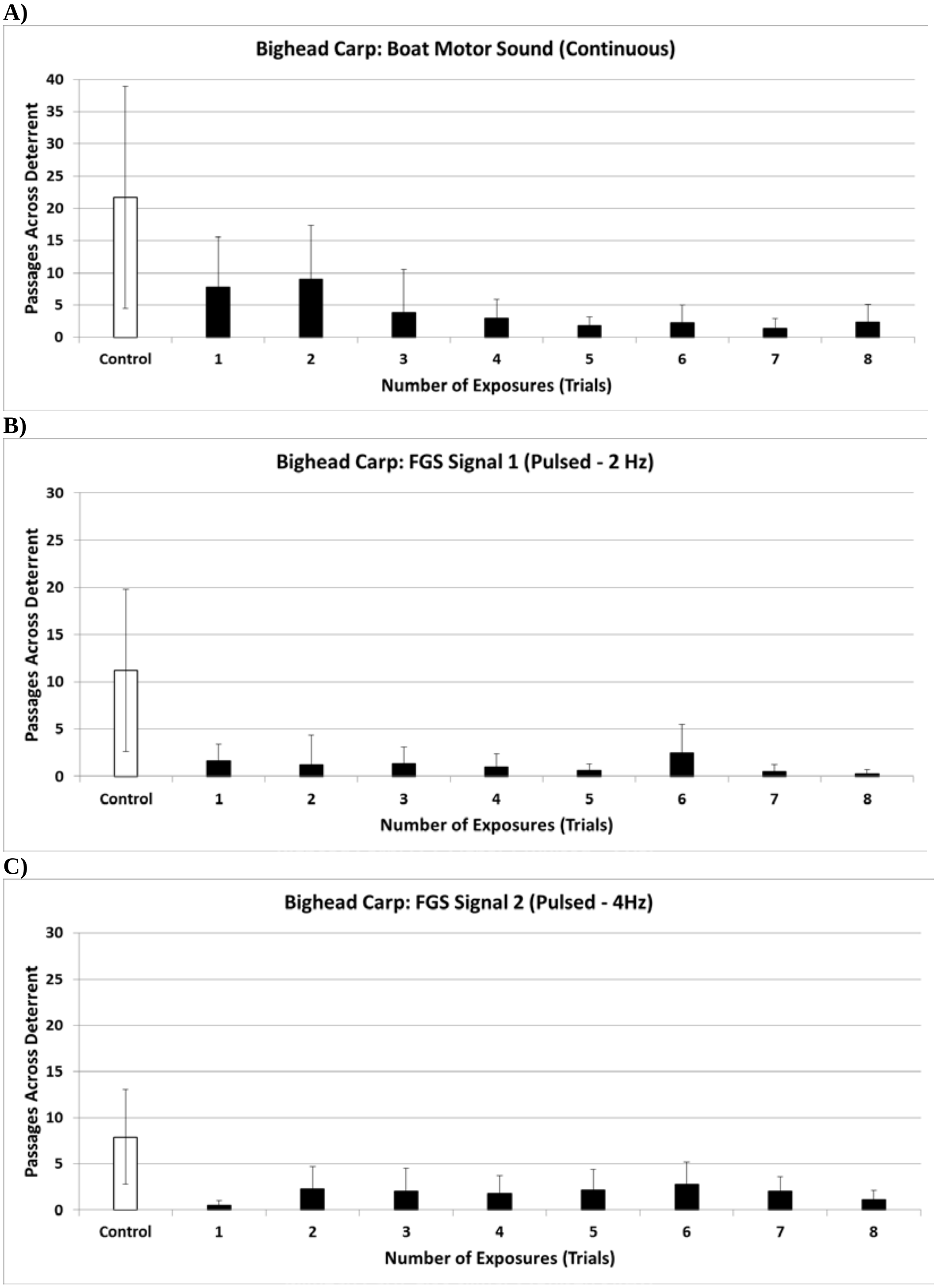


FIGURE 3-12. Passage rates during the typical pre-test control period (white bar: average passage rate of all control periods 1-8) and each Exposure periods (black bars) for bighead carp. Panel A shows results from bighead carp exposed to the outboard Boat Motor Sound, Panel B shows results from bighead carp exposed to the Fish Guidance System (FGS) Signal #1, and Panel C shows results from bighead carp exposed to the FGS Signal #2. N=8 Groups per complex sound treatment.

Final Report Summary:

We completed all activities and evaluated several deterrent systems that might be used in locks in Mississippi River lock and dams to stop invasive (bigheaded) carp passage without significantly affecting native fishes. During the course of this work, which was conducted in both the field and laboratory, we identified a deterrent system / technology, which uses a sweeping pulsed sound with great promise and could potentially stop well over 95% of all bigheaded carps while having little effect on many native fishes. Work to refine this concept is being conducted in the laboratory as part of an ENRTF2013 project and has been proposed for field testing as part of a new LCCMR proposal and a proposal to the U.S. Fish and Wildlife Service (decisions pending). To summarize, initial work in 2015-2016 evaluated the possibility of using hydro-guns and boomer plate technologies to stop carp but a report written for us by Smith Root Inc. showed this approach to be expensive and to have uncertain promise so we have focused since on using underwater speakers and several types of sound while also examining how air curtains might enhance their properties. Our first step was to examine a complex sound produced by an outboard motor. We found that it could deter 50-70% of carp (bigheaded carps are more sensitive than common carp) in both the laboratory and at a field site (the lock at Lock and Dam #1) but that habituation (reduction in responsiveness with repeated exposure) was a concern. The second step was to examine native fish with this promising sound; we found native lake sturgeon did not respond to it but brown trout showed small freezing responses. Next, we sought to refine the sound to minimize the behavioral impact of this sound on trout by modifying the outboard motor sound to frequencies outside their hearing range (1000 – 10,000 Hz) of trout but still within that of carp; we found that while effects on trout were reduced, unfortunately so were those on invasive carp (in the lab). Accordingly, as a fourth step we examined new types of sound including a proprietary commercial signal provided by Fish Guidance Systems Ltd (UK) (20 – 2000 Hz) that is pulsed at a 2 Hz rate through special speakers [hereafter referred to as FGS Signal 1] and another commercial signal provided by Fish Guidance Systems Ltd. (20 – 2000 Hz) that is pulsed at a 4 Hz rate [hereafter referred to as FGS Signal 2]. The FGS sounds show extraordinary promise in our now completed laboratory tests. Both common carp and bighead carp were deterred by both FGS sound at a 80-90% rate. Especially remarkably, habituation was not observed in carps with this pulsed sound and pilot studies with native bass show they are relatively unresponsive while air curtains can enhance the efficacy of this special sound type. We are now conducting laboratory studies to see if we can further enhance this FGS sound system with ENRTF2013 support. Approximatelty $30,000 was not spent for this project because our technican left the project for a new position in outstate Minnesota a few months before the project ended.

ACTIVITY 4: Develop Solutions to Address Weaknesses in Lock and Dam #2 and then Optimize Gate Operation for Lock and Dams #2 through #8

Description: The purpose of this activity is to identify potential weaknesses (scenarios by which carp might swim through the lock and dams) in Lock and Dam #2 (Hastings, MN) and then optimize gate operation to block Bigheaded carps throughout the entire lock and dam system in Minnesota including Lock and Dam #2 through #7 (Lock and Dam #8 is addressed by Activity #1). Lock and Dam #2 is of special interest because it maintains higher velocities than other dams, is ideally situated far from the invasion front, and is located downstream of the Minnesota River. As described in Activity #1, this work will proceed in several steps: 1) development of a 3-dimensional statistical model (computational fluid dynamics [CFD] model) to calculate velocities in and around the dam under a variety of operational conditions and river discharges; 2) acquisition of field measurements of velocities near the dam and use them to validate the CFD model; 3) development and then implementation of a new computational tool to search through 3-D velocity fields to identify specific weaknesses (i.e. swimming pathways) for Bigheaded carps and 4) pairing this information with swimming performance data (Activity #2) to determine how best to block carp passage without causing undue scour ('optimization') and having minimal effects on native fishes (Sturgeon and Trout). Fortunately, Lock and Dams #3 through #8 have similar geometries and operational characteristics so the computational model already developed for Lock and Dam #8 (Activity #1) can be used to optimize these structures. Results will be used in collaborative work with the USACE to develop new gate operation plans that optimally block Bigheaded carps throughout the Mississippi River while minimizing scour and which we fully expect the USACE will consider and then deploy.

Summary Budget Information for Activity 4:

ENRTF Budget:	**$133,951**
Amount Spent:	**$130,059**
Balance:	**$3,893**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. *Develop and validate CFD model of Lock and Dam #2*	August, 2016	$42,063
2.*Identify weakness at Lock and Dam #2 and develop solutions to optimize gate operation based on Bigheaded carps swimming ability (Activity #2), report*	February, 2017	$42,063
3. *Identify weaknesses at Lock and Dam #5 (the most important of the dams located between Lock and dams 3-7) and make set of recommendations to modify its gate operations to stop carp passage*	June, 2017	$87,800

Activity Status as of 2/28/2015:
Work has not yet started (as planned).

Activity Status as of 9/30/2015:
Work has not yet started (as planned).

Activity Status as of 2/29/2016:
Work has not yet started (as planned).

Activity Status as of 8/31/2016:
Work is well underway. A computer model of Lock and Dam #2 has been constructed using original engineering drawings and sub-meter resolution bathymetry data provided by the US Army Corps of Engineers (USACE). This information was used to create 3D computational fluid dynamics models (CFD), and using the University super computing resources we have calculated the velocities and turbulence characteristics of flow through and around the structure. The CFD models contain over 7 million elements and provides velocity data extending 500 ft up-stream and 1000 ft down-stream of the structure. The mean errors between simulation and field data were <5%, thus the CFD model is expected to realistically simulate flow conditions in and around the lock and dam structure for all other river discharges and gate operations. We have validated the CFD model using 3D velocity measurements obtained by the USACE for a river discharge of 94,000 cubic feet per second (cfs). In general, flow is concentrated through the four middle gates and zones of flow recirculation occur downstream of the dam on both sides (Fig. 4-1). The recirculation zone downstream of the hydro facility and abandoned lock chamber offers the greatest potential for fish to approach the dam without expending much energy. To test how and where Bigheaded carp and native fish may pass through Lock and Dam #2, Dr. Dan Zielinski will now model 6 different river discharges ranging from 6,000 – 94,000 cfs as part of his proposed subcontract agreement with the help of Dr. Gilmanov.

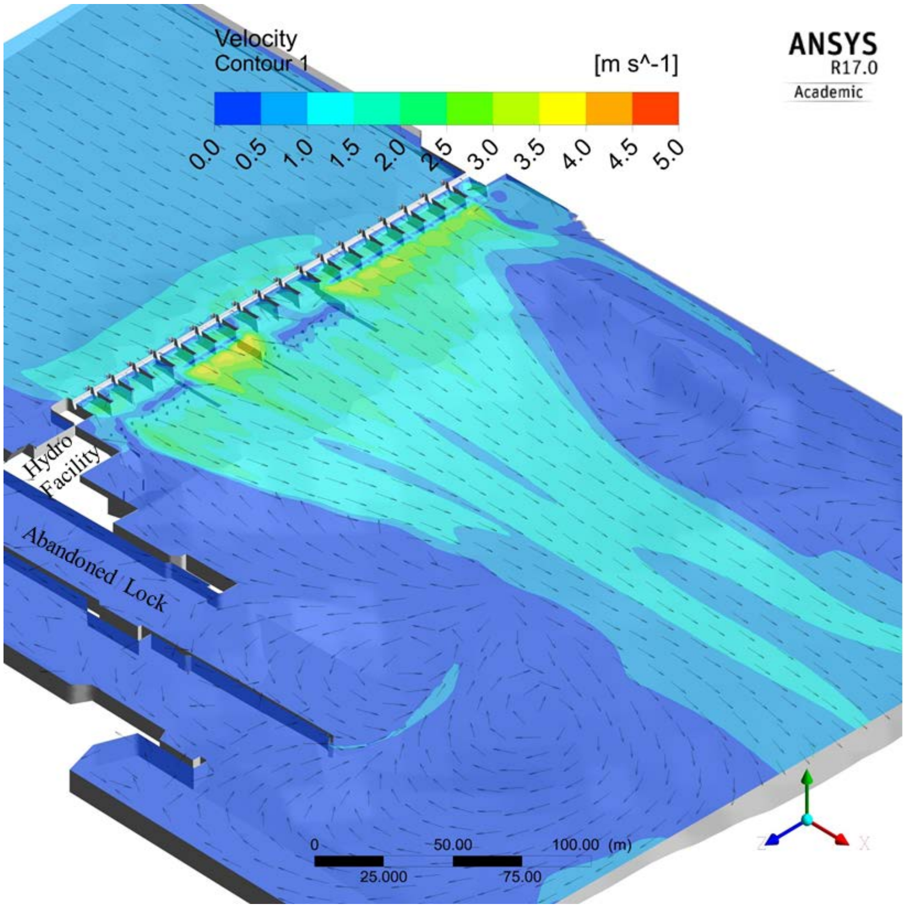


Fig 4-1. Parametric view of Lock and Dam #2 at a river discharge of 45,000 cfs with velocity contour and vector plots.

The CFD models will be now used with our agent-based fish passage model (detailed in Activity Status 9/30/2015 for Activity #1) to identify the likelihood of Bigheaded carp and Lake sturgeon passing through the dam under existing conditions. Based on these results, we will identify changes to gate operation that reduce the likelihood of passage similar to those identified for Lock and Dam #8 (Activity Status 2/29/2016 for Activity #1). Fish passage modelling is well underway and by December 2016 we will present recommendations for changes to gate operation at Lock and Dam #2 to the St. Paul District office of the USACE. Significant improvement in gate operations to block carp that are acceptable to the USACE and will not greatly interfere with native fish passage are envisaged. Consequently, we (Dr. Gilmanov with assistance from Dr. Zielinskipropose to start working on Lock and Dam #5 (the structure with the greatest potential to block carp at a key location). This structure is very large and complex (34 gates) and will require a full-time dedicted effort. Although Dr. Zielinski has left the project for another position he will help guide this process by supplying his codes with the aid of new engineer (Dr. Gilmanov) we will now hire.

Activity Status as of 2/28/2017:

Activity Status as of 2/28/2017:

The numeric modeling effort for Lock and Dam #2 is on schedule and nearly complete. It appears that Lock and Dam #2 already greatly impedes Silver and Bighead carp passage and that modifications to gate operation could further reduce passage by another 50% or so and in a way that the USACE should find acceptable. Briefly, Computational Fluid Dynamics (CFD) models have now been prepared for 8 different river discharges, corresponding to velocity measurements obtained by the USACE in the field with Acoustic Doppler Current Profiler (ADCP) surveys and common carp tracking data collected as part of a complimentary MNDNR funded project. Gate operations at Lock and Dam #2 differ from all other dams on the Upper Mississippi River (including Lock and Dam #8) in that gates are not opened evenly due to disparate downstream scour protection. Lock and Dam #2 also had one tainter gate decommissioned in 1932 due to river bank erosion issues, which increases velocities through the remaining 19 gates. These two factors very likely make Lock and Dam #2 a strong impediment to fish passage and our data show this. Analysis of CFD simulations revealed non-uniform velocity distributions downstream of the dam across all flows, as expected. Because the interior tainter gates are operated first for all river discharges, velocities are highest near the middle of the structure. The depth averaged velocity approximately 30 m downstream of the dam ranges between 0.6-1.0 m/s and with peaks close to 1.8 m/s. Directly beneath the gates, velocities approach 4 m/s during high flows (i.e. large gate openings) and approach 7 m/s during low flows (i.e. small gate opening). Recirculation zones and regions of low velocity occur in front of gates that are not opened during low flows. Although fish cannot pass through the closed gates, these regions provide potential refuge for fish. To quantify the likelihood of fish passage through the dam, we next used the agent-based fish passage model (previously described a "swimming fatigue and pathway selection model"). This fish passage model combines CFD models of fluid flow in and around the lock and dam structures with empirical swimming-fatigue relationships to simulate how and where fish might pass assuming fish will move at an distance maximizing speed and seek the path of least resistance, a worse-case scenario. Results from the model indicate the likelihood of passage (i.e. quantitative analysis of all fish) for a given size of fish and highlights what locations fish may pass through the dam (i.e. visual inspection of fish pathways). Simulations were performed for 11 representative flow conditions between 198-2662 m^3/s (both existing and modified gate operations), using finalized Bigheaded carp swimming data (see details in Activity #2; Hoover etal. 2015). Each simulation used N=5,000 fish of each species to attempt passage through the dam. Size ranges for Silver carp ranged from 500-1000 mm total length (TL), and Bighead carp ranged from 600-1100 mm TL. As a demonstration, we present CFD results and Silver carp passage model simulations (N=50 fish for clarity) for a river discharge of 821 m^3/s under existing and modified gate operation conditions (Figure 4-2 & 4-3). Results in Figure 4-2 and 4-3 are representative of all flow conditions. Under existing operating conditions, both species pass disproportionately more through the lock-side tainter gates than gates near the middle of the dam. Modified gate operations generally reduced the overall number of fish expected to pass (61% in this example) and eliminated passage through the gate closest to the lock chamber (modified conditions at 821 m^3/s close this gate entirely). The modifications to gate operation generally seek to restrict usage of the tainter gate closest to the lock chamber and redistribute flows to the middle 4 tainter gates. For each river discharge and species, we generated length-dependent likelihood of passage estimates.

Population level passage rates were then calculated following the same method outlined in (detailed in Activity Status 2/29/2016 for Activity 1). Table 4-1 provides the global likelihood of passage for Silver and Bighead carp under 8 existing gate operation conditions and 3 modified gate operation conditions. Due to the limited swimming abilities of Bighead carp, Silver carp passage is greater under all conditions. The potential for modifying gate operation are limited under low flow conditions (< 368 m^3/s) because up to 141 m^3/s of flow is diverted through an inline hydropower facility and only a few gates can be opened at the same time. During these conditions, which are nevertheless very rare (see Figure 4-4), the only gate modification possible is to only open 1 gate at a time, which is not permitted by the USACE due to scour risks. Although the model predicts ~10% of Silver carp could pass during low flows, this result is also extremely conservative (i.e produced under-estimates) as passage is only possible by large individuals (total length > 800 mm) which would be unlikely to pass through very small gate openings (~30 cm). Thus although physically possible, actual passage during low flows is likely much lower than predicted. Ongoing work with DNR funding in the field is confirming this (no passage by common carp has been seen). Notably, under higher (and more common) flow conditions (i.e. ≥623 m^3/s) changes to gate operation are possible and reduce Silver carp passage by ~50%. Although the likelihood of passage for both Silver and Bigheaded carp reaches 25-38% during open-river conditions, the dam rarely experiences such discharges (less than a few percent of the time). Notably, the percentage of time flows exceed 1727 m^3/s at Lock and Dam #2 when the gate sopen is approximately 1% (Figure 4-4). The fish passage model was also run for lake sturgeon (*Acipenser fulvescens*), a native migratory fish of importance and well documented swimming abilities. The size range of lake sturgeon used in the model was 1000-1400 mm TL. Passage of lake sturgeon mirror results of bighead carp, with the highest likelihood of passage occurring during open-river conditions. Modifications to gate operation do not appear likely to impact lake sturgeon passage as the likelihood of passage is already less than 0.1% for existing conditions during all discharges less than open-river.

Our next step for Lock and Dam #2 will be to run the model for common carp (*Cyprinus carpio*) using Lock and Dam #2 models in order to validate and better inform initial and boundary conditions of the model using common carp telemetry data collected by the Sorensen Lab as part of a complimentary study funded by the MNDNR. Recommendations for modifications to gate operations at Lock and Dam #2 will then be presented to the USACE for consideration by the next status update and final report.

Table 4-1. Population level passage estimates at Lock and Dam #8 for Silver and Bighead carp under existing and modified gate operations.

River Discharge (m^3/s)	**Silver carp passage**		**Bighead carp passage**	
	Existing	**Modified**	**Existing**	**Modified**
198	10.6%	NA[1]	<0.1%	NA[1]
368	10.7%	NA[1]	<0.1%	NA[1]
623	3.3%	NA[1]	<0.1%	NA[1]
821	16.6%	6.5%	0.5%	<0.1%
1048	10.1%	4.4%	0.3%	<0.1%
1274	17.7%	1.7%	1%	0.3%
1727 (open-river)	38.3%	NA[2]	26.1%	NA[2]
2662 (open-river)	25.9%	NA[2]	12.1%	NA[2]

NA[1] - no modifications were simulated because large portion of flow passes through the hydropower facility, greatly limiting possible changes to gate operation (see text for full explanation). This flow condtions are associated with low gate openings (further reducing possible passage) and are relatively uncommon (see Fig. 4-3).

NA[2] - no modifications were simulated because all gates must be out of the water during open-river conditions

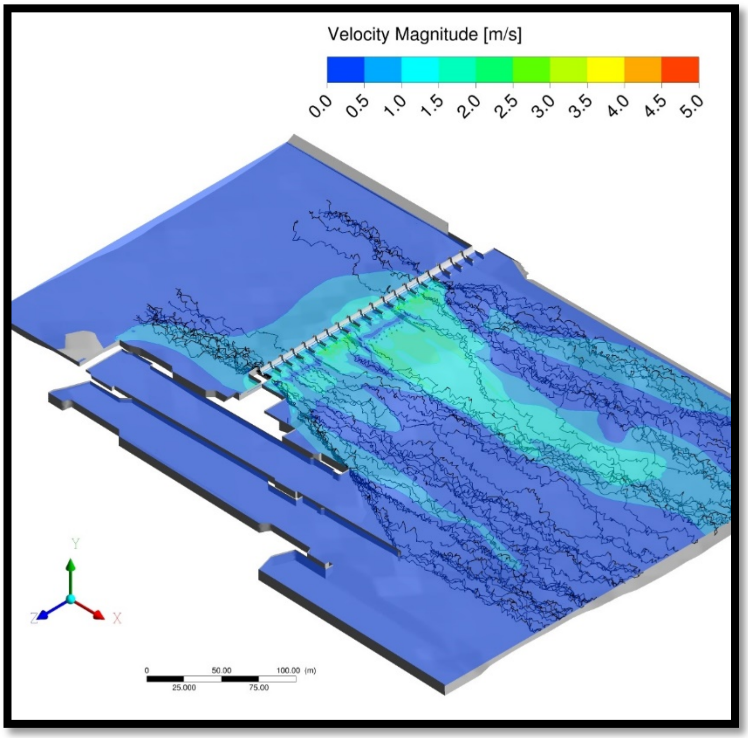


Figure 4-2. Velocity magnitude contours at the surface and N=100 simulated Silver carp pathways up to and through Lock and Dam #2 at river discharge 821 m^3/s under existing gate operations.

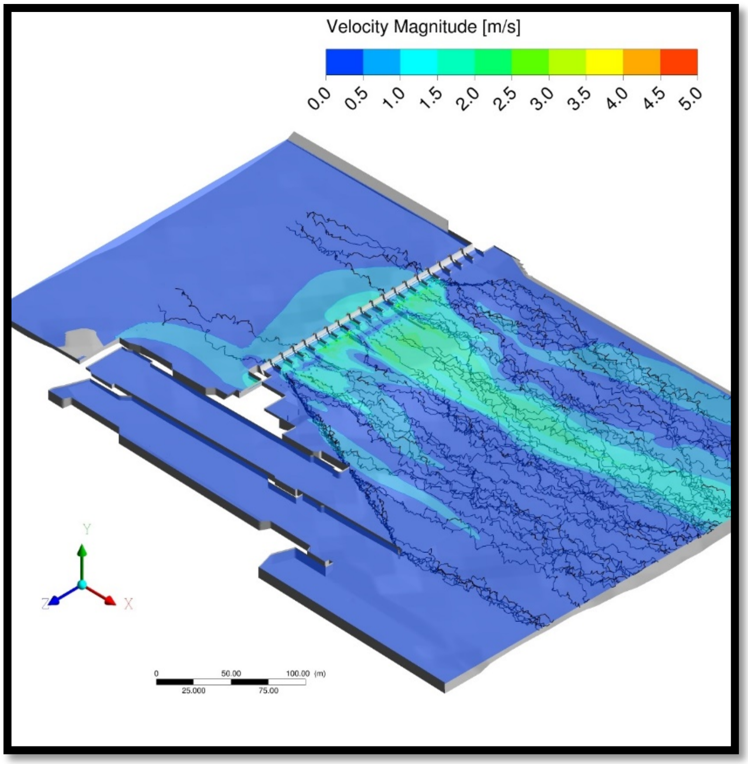


Figure 4-3. Velocity magnitude contours at the surface and N=100 simulated Silver carp pathways up to and through Lock and Dam #2 at river discharge 821 m^3/s under modified gate operations.

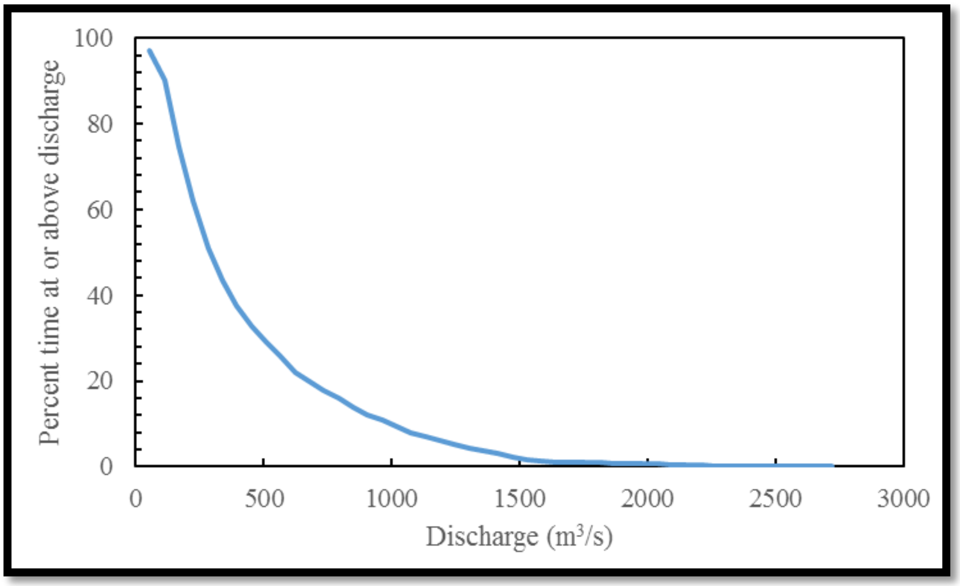


Figure 4-4. Percent time at or above indicated discharge at Lock and Dam #2. [Figure modified from USACE Lock and Dam #2 Water Control Manual]

Finally, work is now underway developing a computational model that will be able to simulate passage of Bigheaded carp and native fish through the gated portion of Lock and Dam #5 by Dr. Gilmanov. The Computational model, which was previously developed by Dan Zielinski in application to Lock and Dam #8 (see Activity Status of 2/29/2016) was used as the base concept to investigate functioning of Lock and Dam #5. We began this work by constructing a computer model of the lock and dam structure using engineering drawings and bathymetry data provided by the US Army Corps of Engineers (USACE). On Fig.4.5 the model of Lock and Dam #5 is shown. This model will be used to create a 3D computational fluid dynamics model (CFD) using University super computing resources to calculate the velocities and turbulence characteristics of flow through and around the structure. We are on schedule to make initial recommendations on changes to gate operation to maximize velocities without increasing scour (thereby slowing carp movement) to the USACE in June 2017. Evaluation of modeling potential will be dicussed in our next and final report.

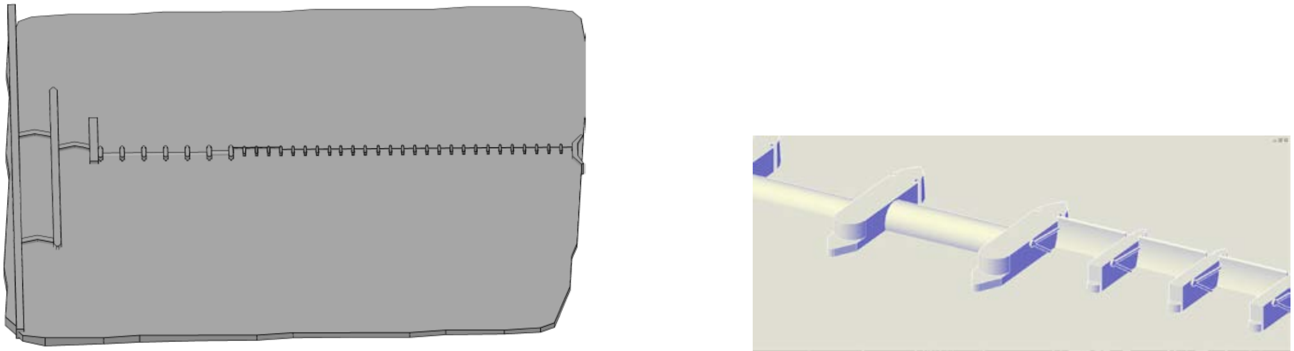
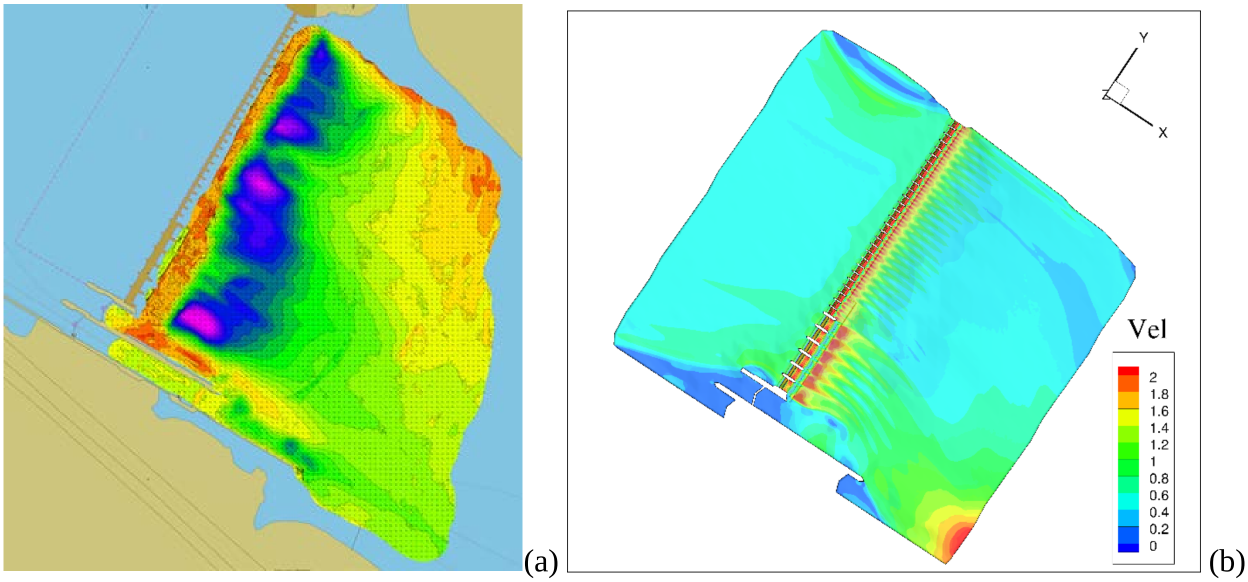

(a) (b)

Fig. 4.5 Geometry of Lock and Dam #5 (a) and local fragment with roller and tainter gates (b).

Activity Status as of: 6/30/17

Using computational agent-based modeling we have identified a series of weaknesses in gate operations at Lock and Dam #5 that which might allow bigheaded carp to pass as well as a series of initial solutions. We have communicated this understanding with the U.S. Army Corps of Engineers (USACE) and suggested that we are available to meet and discuss them as soon as possible (likely this fall).

Meanwhile the USACE has reviewed and officially approved our suggested changes in their gate operations for Lock and Dam #8. Final approval of these changes took three meetings and several models and we expect this to be the case again, especially given the large size and complexity of this lock and dam It has 6 roller gates and 28 tainter gates). Our new recommendations for Lock and Dam #5 (Table 4-2) should reduce bigheaded carp passage by at least 50% from current rates with the possibility of further adjustments/improvements. As with Lock and Dam #2 (and Lock and Dam #8) work proceeded in several steps. Initial computational fluid dynamic (CFD) modelling of Lock and Dam #5 discovered that flow fields through this structure are uneven because of uneven bottom topography and extant gate operations which favor flow through the roller gates- i.e. there is considerable room for improvement to reduce carp passage and scour (Fig. 4.6). This modelling effort was complex and 3D nonsteady Navier-Stokes equations with κ-ε turbulent models were solved with ANSYS-FLUENT (Fig. 4-7). The computational region was discretized with 1-3 million tetrahedrons elements.



(a) (b)

Fig.4.6 *Bathymetry in the vicinity of L&D#5 (a) and CFD solution (b) of fluid velocity contours in computational region.*

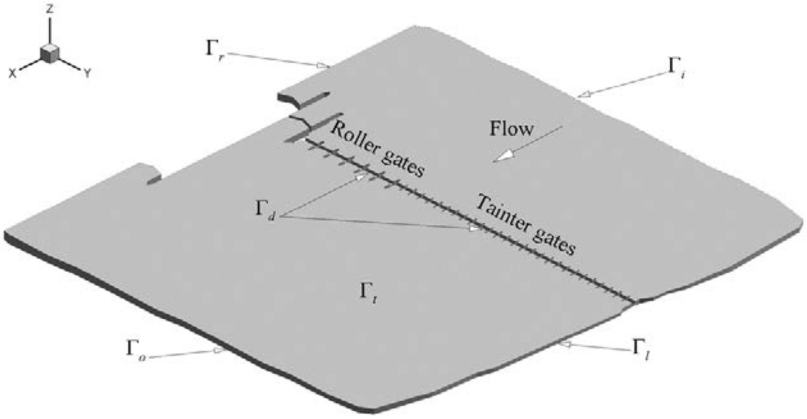


Fig. 4.7 *Model structure of Lock and Dam #5 showing major surfaces of computational region:* Γ_i, Γ_o *are input and output surfaces;* Γ_l, Γ_r, Γ_t *are left, right and top surfaces;* Γ_d *is surface of lock and dam,* Γ_b*.is surface of bottom is not shown. The dimensions of the computational region are* $L_x = 632\ m$ *and* $L_y = 600\ m$ *in* Ox *and* Oy *directions, respectively.*

The agent-based model of fish swimming described in our previous reports and created by Dr. Zielinski was next been used to simulate carp trying to pass through the dam after we had identified five flow regimes based on flow data provided by the USACE for 2011 (Fig. 4-8). We found that low flows and developed a coefficient of effectiveness of gate regulation as a ratio $K = \%L_{old}\ /\ \%L_{new}$, where

$\%L_{new}, \%L_{old}$ percent of fish passage for new and old gate regulations. Our models deployed silver carp as a worst case scenario because they are better swimmer than bighead carp.

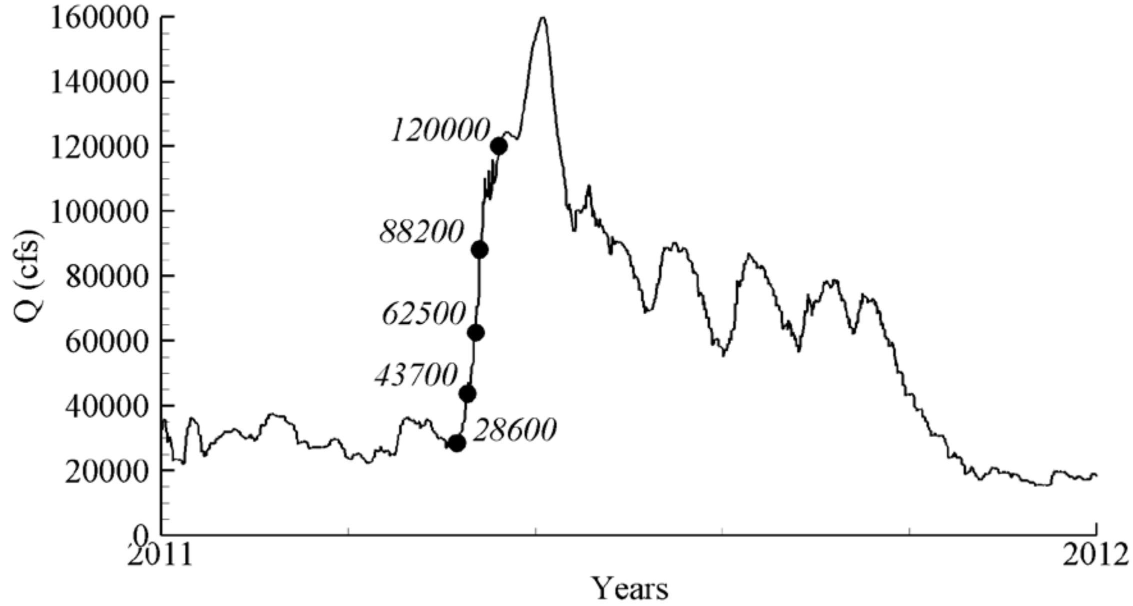


Fig. 4-8 *Flow discharge on the Mississippi River at Lock and Dam #5 during 2011. Black dots indicate cases (variants), which we analyzed in our investigation by providing simulations of fluid flow and fish passage through the. Note that spillways gates are raised out of the water at flow discharge $Q > 116K\ cfs$, facilitating fish passage.*

We analyzed carp passage rates for all five flow regimes and then developed possible solutions to reduce this by altering gate heights. For brevity we, summarize two of these (Q=88200 cfs; here by the USACE will receive full details. In our simulations we considered five different sizes of fish: $S_i = 0.6, 0.7, 0.8, 0.9, 1.0\ (m)$ based on carp population from the Wabash River. Techniques floowled those outlined in our previous report (detailed in Activity Status 2/29/2016 for Activity 1 and 2/29/2017 for Activity 4). Initial positions of fish on the input of computational region ($x = x_0$) were random. Solutions of 3D flow fields around L&D#5 for current and modified spillway gate configurations are shown in Fig.4-9 and 4-10 for 88,200 cfs. For the current spillway gate configuration, all spillway gates are open at a level of $H = 5ft$, except the last 7 tainter gates which are at $H = 4.5ft$. The total sum likelihood of carp passing at this setting is $L_0 = 26\%$ which when broken up by fish size (m): $L_{0.7}$~5%, $L_{0.8}$~18%, and $L_{0.9}$~2%, (Fig 4-11). Fig 4-12 shows simulations with modified gate operation. This modification reduce sum passage to to $L_0 = 15\%$ with coefficient blocking of fish passage $K = 1.7$ Fig. 4-12) – almost a 50% reduction.

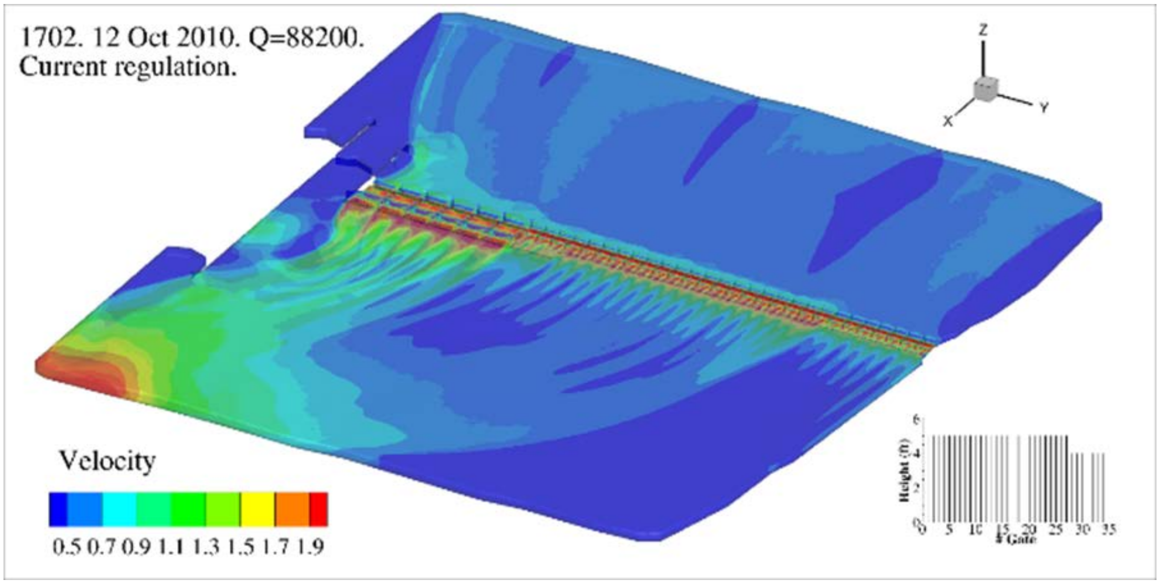


Fig. 4-9. *Contours of velocity flow in the computational region around L&D#5 for current gate regulation with Q=88200cfs. The small fragment (left-bottom) indicate used gate regulation (see explanation below).*

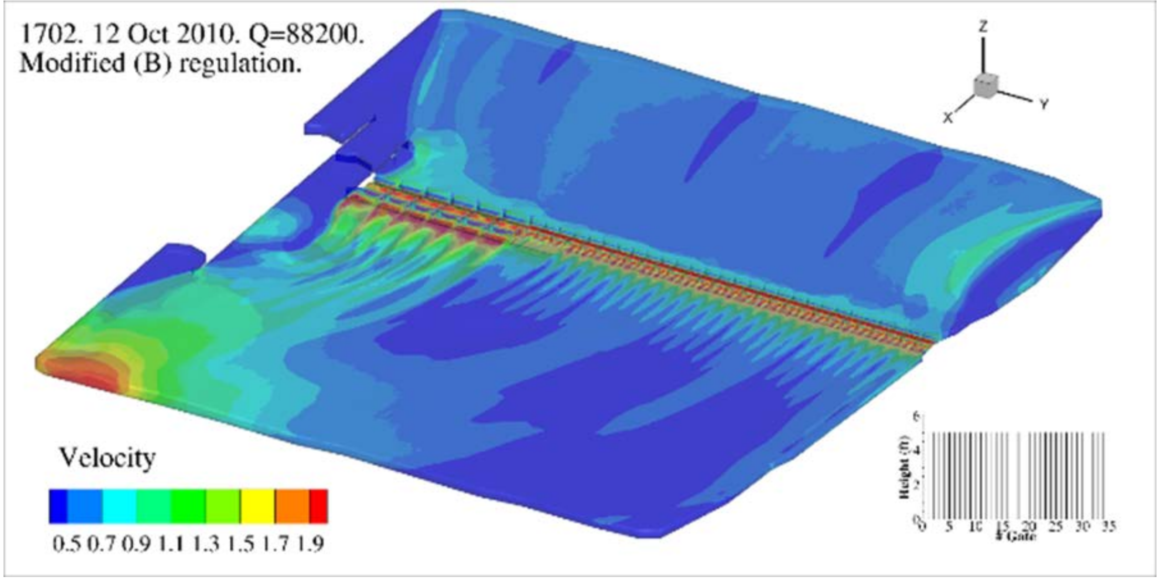
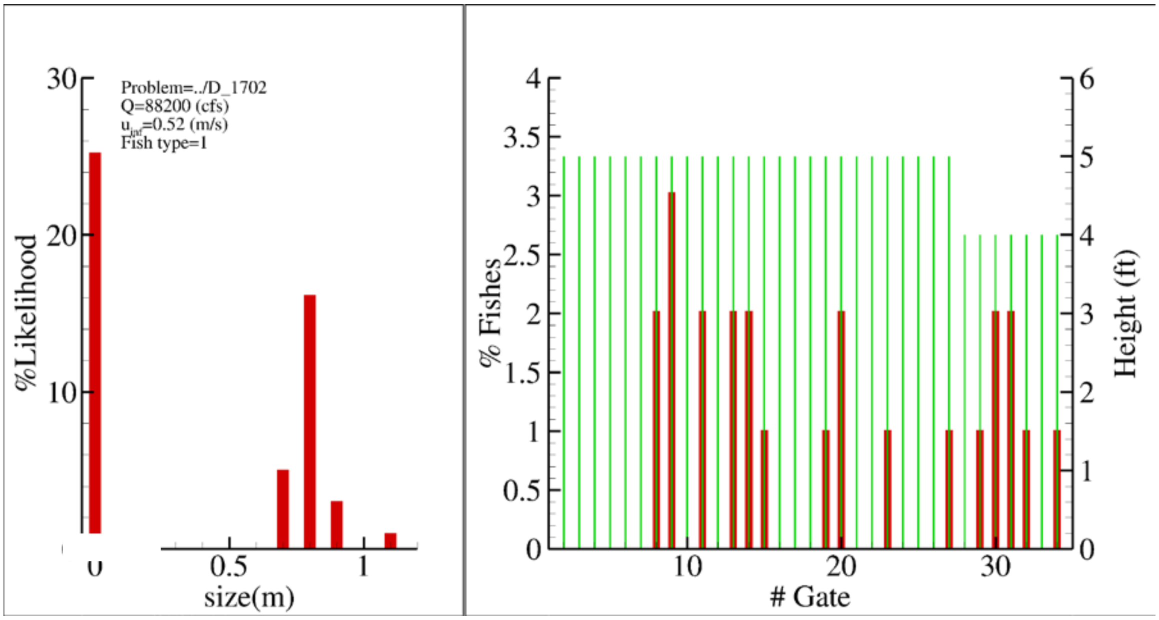


Fig. 4-10. *Contours of velocity flow in the computational region around L&D#5 for modified gate configurations with* $Q = 88.2K\ cfs$*. The small fragment (left-bottom) indicate gate regulation (see explanation below).*



(a) (b)

***Fig 4-11**. Results of silver carp passage for current gates operation with $Q = 88.2K\ cfs$. First bar on the left figure (a) (%Likelihood) indicates sum of likelihood fish passage for all sizes $\%L_0 = \%L_{0.6} + \%L_{0.7} + \%L_{0.8} + \%L_{0.9} + \%L_{1.0}$, the other bars indicate likelihood of fish passage for specific fish size L_s. Green bars on the right figure (b) show gate regulations, which indicate level/height of roller and tainter gates (Height (ft)) depends of gate number (#Gate) and red bars indicate at percent of fishes (%Fishes) passed through the specific gates (#Gate). One can see that maximum fishes (about 3%) passed through the tainter gate #9.*

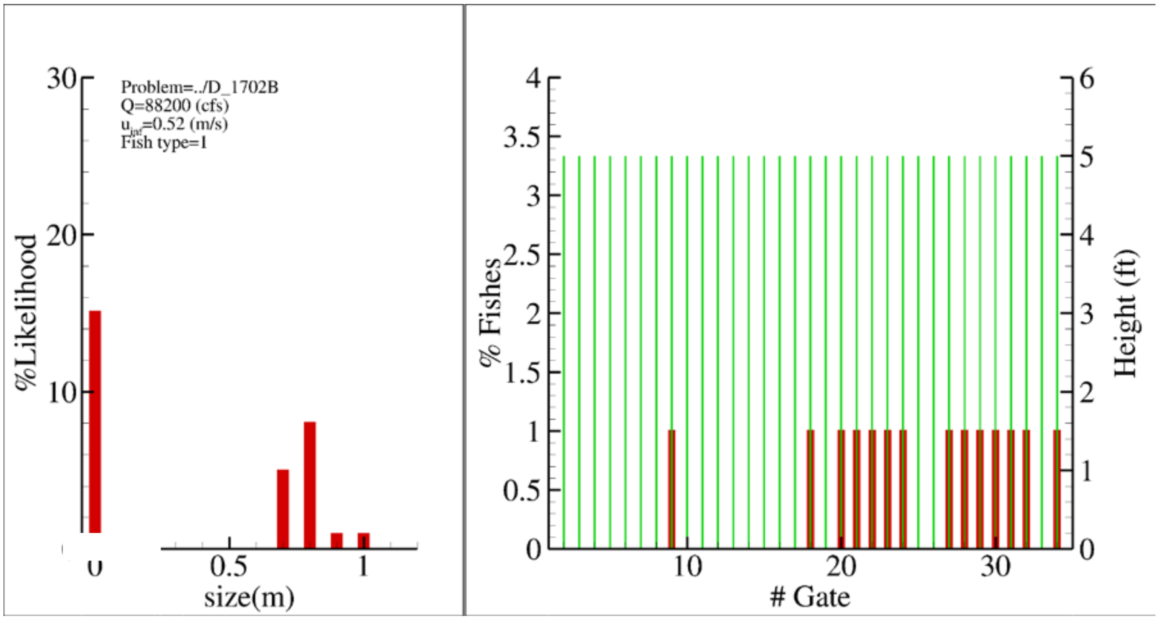


***Fig.4-12.** Results of Silver Carp passage for our recommended modified gates operation at $Q = 88.2K\ cfs$. See explanations in Fig.4-11.*

In our second example, simulations of $Q = 28.6$K cfs (which occurs only in the winter when fish may not be moving) showed a total sum passage rate of $\%L_0 = 70\%$ under current operating conditions. This rate is so high because of water piling up and creating vortices by the roller gates at low flows (Fig 4-13). Closing different sets of gates created improvements with one of the best scenario being to close 4 tainter gates, leading to an overall passage rate of about 40% (Fig. 4-14). We will explore other combinations with the USACE when final recommendations are presented and developed. Meanwhile, similar modeling efforts are now underway for Lock and Dam #4, the next structure upstream which is both highly amenable to such changes and could be sued in tandem with changes in Lock and Dam #4, completing this project.

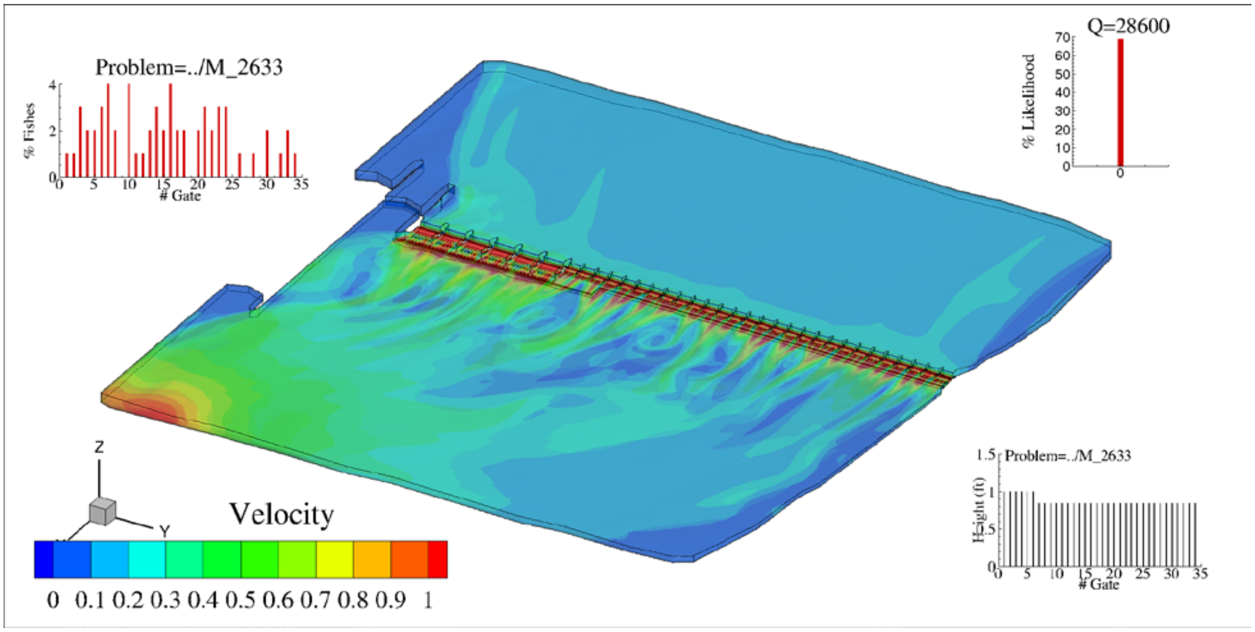


Fig. 4-13 *Mean regulation of gates for* $Q = 28.6K\ cfs$. *Contours are magnitude of mean velocity in the computational region. Top-left sketch is % of fish passed (% Fishes) through the corresponding gates (# Gates). Top-right sketch is a total likelihood of fish (*$\%L_0 = \%L_{0.6} + \%L_{0.7} + \%L_{0.8} + \%L_{0.9} + \%L_{1.0}$*) passed through all gates. Here* $\%L_0 = 70\%$. *Bottom-left sketch is gate operation (opening roller and tainter gates in feet).*

Examining suggested changes at all 5 flow conditions (except for open river), we can realize about a 50% reduction in total carp passages (Table 4-2).

Table 1. Population level passage estimates at Lock and Dam #5 for Silver and Bighead Carp under existing and modified gate operations.

River Discharge (cfs)	**Silver Carp Passage**	
	Existing	**Modified**
120.0 K	54%	NA
88.2K	26%	15%
78.3K	26%	16%
62.5K	48%	26%
43.7K	50%	31%
28.6K	70%	40%

In conclusion, our computational model has provided recommendations for new gate operating regulations of Lock and Dam #5 that could block at least an additional 50% of all invasive carps passing this key structure. Because the number of carp passingthis structure is already very low (only handful of carp are captured very year up stream), this would be very significant. Uther improvements are also possible by closing more gates but these possible actions will demand more intensive and careful investigation. The USACE has signaled they will consider them with us.

Final report Summary

We performed initial analyses of Locks and Dam #2 through #8, and concluded based on both their physical attributes and how often their spillway gates come out of the water (a time when water flows drop and carp can pass – and gate changes are not possible), that of these structures, Locks and Dams #2, #4, #5 and #8 had special promsie. These three structures were then examined in closer detail usinf computational models. Using computational agent-based modeling we identified a series of weaknesses in gate operations at Lock and Dam #8 and impliemented solutions for them with the USACE (see also Activity #1). A similar set of analyses and conclusions were reached for Lock and Dam #2 and #5 and presented to the USACE. Although carp passage rates are relatively small at Lock and Dam #2 (at most flows, about 2%) and it is not clear yet if the USCAE will take action, this is not the case for Lock and Dam #5 where passage rates might be as high as 50%, so gains (projected to reduce passage by 50-66%) by adjusting gates much greater. The USACE is presently evaluating these possibilities as well as our intial data for Lock and Dam #4 (which is still be developed as part of ENRF2012). In all cases, our models and suggested changes should reduce carp passage by at least 50% which is highly significant given the fact that very few carp pass locks and dams at present and these changes can be made at no cost.

V. DISSEMINATION:

Description:
Results will be disseminated through technical reports to the USACE, scholarly publications in peer-reviewed journals such as *Fisheries Management and Ecology*, *Water Resources Research*, and *Ecological Modeling*. Results from the research project will also be presented at regional and national conferences such the *American Fisheries Society* conference. Results will also summarized on the Minnesota Aquatic Invasive Species Research Center's Webpage and Facebook pages.

Activity Status as of 2/28/2015:
Preliminary results have not yet been disseminated.

Activity Status as of 8/31/2015:
Presentations have been made on the modeling studies. These include presenations to the USACE (2), MN American Fisheries Society and the National Chapter of the American Fisheries Society. A presentation was also made ot the International meeting on Fish Passage (Netherlands) but other funds were used for this. A presentation was also given and a field session hosted at the 2015 MAISRC Showcase.

Activity Status as of 2/29/2016:
Presentations have been made on the modeling studies and sound studies. These include presenations to the USACE (1) and Mississippi River Basin Aquatic Nuisance Species Task Force (1). A study on sound was accepted for publication but the citation is not yet available.

Activity Status as of 8/31/2016:

Presentations have been made on the modeling studies and sound studies. These include 5 presenations to the national American Fisheries Society meeteings at a symposium on fish detrrents that we organized. One paper was published:

Zielinski, D. P., and P. W. Sorensen. "Bubble Curtain Deflection Screen Diverts the Movement of both Asian and Common Carp." *North American Journal of Fisheries Management* 36.2 (2016): 267-276.

Activity Status as of 2/28/2017:

A manuscript has been written and submitted to PlosOne on the role of particle motion in sound deterrence in carps (Zielinski and Sorensen).

We made two presentations;
Clark, D, Sorensen, P, Turnpenny, A. Sorensen, PW. 2017. A broadband complex sound effectively blocks carp passage. Minnesota Chapter of the American Fisheries Society, St Cloud.

Gilmanov, A., Zielinski, D., Sorensen, PW 2017. Computational agent-based model of fish swimming through Mississipppi River locks and dams. Minnesota Chapter of the American Fisheries Society, St Cloud

Hoover, J.J, Zielinski, D.P, and P.W. Sorensen 2016. Swimming performance of adult bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845) and silver carp *H. molitrix* (Valenciennes, 1844). Applied Ichthyology 206: 1-9.

Activity Status as of 6/30/2017:

We gave three presentations: one to the Mississippii River Cooperative Resource Association, one to the MN DNR, and another to the Internationl Fish Passage Conference (Portland Oregon) . In addition, we published two more peer-reviewed papers:

Zielinski, D. and Sorensen, P.W. 2017. Silver, bighead and common carp orient to particle motion while avoiding a complex sound. PLoS ONE 12(6): e0180110.

Escobar LE, Mallez S, McCartney M, Zielinski DP, Ghosal R, et al. Aquatic Invasive Species in the Great Lakes region: An Overview. *Reviews in Fisheries Science & Aquaculture* (In Press), 2017

Final Report Summary:

Over the past three years, we made well over two dozen professional presentations, including 14 presenations to scientific groups. We have also published four peer-review scientific publications and now have another in review. Results have also been summarized on the Minnesota Aquatic Invasive Species Research Center's Webpage and Facebook pages and in newsletters..

VI. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview:

*This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report. See the Sub-Project Budget document for an up-to-date project budget, including any changes resulting from amendments.

Budget Category	$ Amount	Explanation
Personnel:	$ 412,677	Faculty: 6 weeks $18,600; 0.12 FTE Faculty: 2 weeks $12,000; 0.08 FTE Professional & Admin: $65,654 x 1 yr; 1 FTE) Post Doctoral Fellow: $60,600 x. 1.5 yr; 1.5 FTE Scientist: $48,000 x 2.25yr; 2.25 FTE

		Undergraduate: $2,000 (180 hrs) 0.1 FTE Undergraduate: $24,000 (20h/wk x 100 wk); 0.62 FTE
Professional/Technical/Service Contracts:	$326,651	(1) Services- office & gen oper. costs that are specific to the project $1,100 (printing/duplication, shipping, etc.) (2) Professional Services- lab & medical (Super-computing Intsitute (MSI) Resources) $2000 (3) Professional Services & contracts- Activity 2: $150,000 (US Army Corps of Engineers, Swimming performance tests of adult Bigheaded carps at Engineer Research and Development Center in Vicksburg, MS (Activity #2): Jan Hoover (Research Fisheries Biologist). Cost includes: Personnel (91%), Travel to field site (5%), Misc. equip. for swim tunnel (4%)) (4) Professional Services & contracts- Activity 3: $20,000 DNR: 1 field technician and electrofishing boat(8mo over 2 summers) (5) Professional Services & contracts- Activity 3: $17,658 Smith Root Inc Pilot hydrogun test and predesign report (Senior biologist and travel) (6) Professional Services & contracts- Activity 3: $130,993 Smith-Root Water gun and boomer plate tests with report (6 wk equipment, supplies, biologist, technician; or UofMn Hydro) (7) Repairs- lab & field ACTIVITY 1: (speaker repair), ACTIVITY 3: various repair $4,900
Equipment/Tools/Supplies:	$59,804	(1) Supplies- office & gen oper. costs that are specific to the project (Software - modeling, misc. office supplies) $500 (2) Supplies- lab & field ACTIVITY 3: $47,054(Fish for lab and field experiments; fish holding supplies (food, nets, filters, etc); fish behavior supplies (cameras, recording devices); 2 x 200ft of 14/3 SO Cable for transducers; 2 Pontoon floats and supplies ($1000 ea)- for transducers; 150 radiotags (ATS F1835C - could also be accoustic)- fish radio tracking @$164.70; 1 receiver case (ATS)- fish radio tracking; AC-DC power supply (ATS)- fish radio tracking; coaxial cable for antennas-fish radio tracking; surgical

		supplies for implanting tags (sutures, scalpels, anethestec); misc field supplies; misc lab supplies) (3) Equipment- non capital lab & field ACTIVITY 1: $1,500 (Computer (high powered desktop)-modeling,) (4) Equipment- non capital lab & field ACTIVITY 3: $10,750 (11x Ant switchbox (x11) (14219 ATS)- fish radio tracking; 2 divider nets (12 x 60ft);Laptop Computer - for data collection;2 x CDi2000 amplifier to drive transducers ($1300 ea) – implementation;C75 Hydrophone and calibration ($1800 ea)- accoustical measurement for transducers;Portable recording device for use with hydrophone)
Capital Expenditures over $5,000:	$33,800	(1) Cap expenditures over $5,000: ACTIVITY 3: 2 LL1424HP under water transducers ($8200 ea) - implementation, 3 Coded receiver datalogger- fish radio tracking ($5,800ea) (2)
Other	$2,800	(1) Research-specific utilities ACTIVITY 1: (electricity to power transducers at Lock & Dam #8 (approx. cost 2 of 3 years), charge for phone line for alarm)
Travel:	$18,268	(1) Travel - MN ACTIVITY 1: $2,468 (8 trips (LD 8) x 350 miles/trip x 0.56/mi); Lodging (200/person/wk x 2days);Conference (Travel and Lodging) for researcher to formally present research findings and gather information on new advances in the field) (2) Travel - MN ACTIVITY 3: $2,628 38 wks x 100miles/wk x 0.56/mi), Conference Travel and Lodging (x2) for researcher to formally present research findings and gather information on new advances in the field; (3) Travel - MN ACTIVITY 4: $672 6 trips (LD 2) x 200miles/trip x 0.56/mi) (4) Travel - Domestic ACTIVITY 1: $2,500 Conference (Travel and Lodging) for researcher to formally present research findings and gather information on new advances in the field (5) Travel - Domestic ACTIVITY 2: $2,500 (Airfare to Vicksburg, MS (2 x 600), Travel

		in Vicksburg, MS (a car x 1 wks), Lodging (1000/person/wk x 4 days)) (6) Travel - Domestic ACTIVITY 3: $5,000 Conference (Travel and Lodging) for researcher to formally present research findings and gather information on new advances in the field (7) Travel - Domestic ACTIVITY 4: $2,500 Conference (Travel and Lodging) for researcher to formally present research findings and gather information on new advances in the field **The scientific conferences budgeted here are for the researchers (only) to participate in formal presentations of project findings, as required by LCCMR policy. One of the most important ways for scientists to get ideas and feedback for advancing their work is to attend and present at scientific conferences. Conferences provide a unique and critical opportunity for exchange of ideas that will likely lead to higher quality techniques, approaches, and outcomes on this project.**
TOTAL ENRTF BUDGET:	**$854,000**	

Add or remove rows as needed

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000:
High-amplitude transducers ($8200 ea) are needed to safely produce sound that can repel carps in locks chambers. The two transducers are requested here for experiments at Lock and Dam #1 (Activity #3), and serve as back-ups for the system installed at Lock and Dam #8. 3 Coded receiver dataloggers ($5800 ea) are needed for fish radio tracking during the acoustic deterrent testing in the lock chamber at Lock and Dam #1. Kraken cabled tracking system ($28,000) is needed to track the fish. A FPZ K12-TD-GOR-50 Blower and attachments ($7,000)is needed to run the experimental air curtain at Lock and Dam #1 (Activity #3). After which time the dataloggers and any equipment not permanently installed in situ for carp deterrence will continue to be used for invasive carp research at the Minnesota Aquatic Invasive Species Research Center.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:
5.7 FTE

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:
4.25 FTE

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			

US Army Corps of Engineers	$10,900	$10,900	For preliminary tests of Bigheaded carps swimming ability using the USACE swim tunnel in Vicksburg, MS, in Fall 2013
Smith Root Inc	$250,000	$0	In kind support including technician and equipment use (dollar value is an estimate and will not be tracked in this workplan)
ATS	$80,000	$0	In kind support including technician and equipment use (dollar value is an estimate and will not be tracked in this workplan)
State			
2012 ENRTF MAISRC	$69,700		For expedited purchase and installation of transducers at L&D #8
Private			
	$5,300	$	For expedited purchase and installation of transducers at L&D #8
TOTAL OTHER FUNDS:	**$ 415,900**	**$10,900**	

VII. PROJECT STRATEGY:

A. Project Partners:

US Army Corps of Engineers (USACE) - St. Paul (MN) office (R. Snyder): The USACE is providing us with all of their data from all lock and dam structures and offered to get more gratis. Their engineers will also review all of our models and work with us on reports. Additionally, they have offered to help maintain transducers at Lock and Dam #8. Full access for two years has been granted to the auxiliary lock chamber at Lock and Dam #1 along with limited technical support gratis. They already funded a Bigheaded carps swimming study for us. Finally, and most importantly, they will consider the possibility of implementing all suggestions from reports we generate together on lock and dam operations. All assistance is gratis. (Activities #1,2,3 and 4)

US Army Corps of Engineers (USACE) – Vicksburg (MS) office (Dr. J. Hoover): The USACE will conduct Bigheaded carp swimming tests at cost ($150,000 contract). (Activity #2)

MN DNR- St. Paul (MN) office (Nick Frohnauer). The MN DNR will provide one part time technician to help run experiments at Lock and Dam #1 (Activity #3) at cost ($20,000 contract). (Activity #3)

Smith Root Inc. (SRI) – Vancouver (WA) office (Dr. Jackson Gross). SRI is providing us with over $100,000 of biologist and technican time and approximately $150,000 of acoustic equipment for use in testing in Activity #3 as in-kind match. We will fund two contracts with them at cost, one for approximately $17,000 for a pre-report and set of recommendations on acoustic deterrent tests, another for about $130,000 if such tests are conducted. (Activity #3)

Advanced Telemetry Inc. (ATS) – Isanti (MN) office (Jon Amseth). ATS has offered to provide us with several weeks of engineering help gratis setting up fish tracking devises for Activity #3. They are also offering to provide us with nearly $80,000 of tracking equipment gratis and provide help with data analysis. (Activity #3).

US Fish and Wildlife Service: The USFWS has agreed to monitor fish movement in front of Lock and dam #8 for us using acoustic telemetry.

B. Project Impact and Long-term Strategy: This project will protect the Upper Mississippi, Minnesota, St. Croix rivers and their tributaries from the threat of Bigheaded carps while preserving native fish populations. Initially, this is accomplished by providing US Army Corps of Engineers with new operating procedures for lock and dams as well as recommendations for sound deterrents. With additional funding, modeling could eventually be conducted to maximize native fish passage. This project is a natural extension of previous work on fish deterrent systems and of current work at the Minnesota Aquatic Invasive Species Research Center to protect Minnesota's waters from invasive species including Bigheaded carps.

C. Spending History:

Funding Source	M.L. 2008 or FY09	M.L. 2009 or FY10	M.L. 2010 or FY11	M.L. 2011 or FY12-13	M.L. 2013 or FY14
ENRTF M.L. 2009 Chp.143, Sec. 2, Subd. 6d.		300,000			
Ramsey Washington Metro Watershed District: $207,600 (Common carp control, $100, 000 for barriers)		100,000			
Clean Water Fund M.L. 2012 Chp. 264, Art. 2, Sec 4 (for the MAISRC)				1,800,000	
ENRTF M.L. 2012, Chp. 264, Art.4, Sec. 3 (for the MAISRC)				2,000,000	
ENRTF M.L. 2013, Chp. 52, Sec. 2, Subd. 06a (for the MAISRC)					8,700,000

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. VISUAL ELEMENT or MAP(S): Attached

X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: N/A

XI. RESEARCH ADDENDUM: Attached

XII. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than 2/28/2015, 8/31/2015, 2/29/2016, 8/31/2016, and 2/28/2017. A final report and associated products will be submitted between June 30 and August 15, 2017.

Environment and Natural Resources Trust Fund
M.L. 2014 Project Budget Aquatic Invasive Species Research Center
Project Title: Blocking Bighead, Silver, and Other Invasive Carp by Optimizing Lock and Dams
Final Report
Project Manager: Peter Sorensen
Organization: University of Minnesota – Minnesota Aquatic Invasive Species Research Center
M.L. 2014 ENRTF Appropriation $ 854,000
Project Length and Completion Date: 3 Years, June 30, 2017
Date of Report: September 23, 2017

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	*Activity 1: Immediate Development and Implementation of a Deterrent Strategy for Lock and Dam #8*			*Activity 2: Quantify Adult Bigheaded Carps Swimming Capabilities*			*Activity 3: Test and Develop New Acoustical Deterrent Systems for Locks*				*Activity 4: Develop Solutions to Address Weaknesses in Lock and Dam #2 and then Optimize Gate Operation for Lock and Dams #2 through#8*							
BUDGET ITEM	**Activity 1 Budget**	**Amount Spent as of 9/15/16**	**Activity 1 Balance**	**Activity 2 Budget**	**Amount Spent as of 09/15/16**	**Activity 2 Balance**	**Activity 3 Budget**	**Activity 3 Revised Budget**	**Amount Spent as of 8/31/17**	**Activity 3 Balance**	**Activity 4 Budget**	**Activity 4 Revised Budget**	**Amount Spent as of 8/31/17**	**Activity 4 Balance**	**TOTAL BUDGET**	**TOTAL REVISED BUDGET**	**TOTAL SPENT**	**TOTAL BALANCE**
Personnel (Wages and Benefits) - Total (Estimates)	$128,096	$128,096	$0	$0	$0	$0	$225,040	$225,040	$224,521	$519	$121,073	$121,073	$119,080	$1,993	$474,209	$474,209	$471,697	$2,512
Professor: Peter Sorensen $21,800 salary, $7,399 fringe (33.7 % fringe rate) 0.12 FTE Total [8 weeks total: 1 wk Activity 1, 1 wk Activity 2, 4 6 wks Activity 3, 1 week activity 4]																		
Professor: Vaughan Voller $15,100 salary, $3,234 fringe (33.7% fringe rate) 0.08 FTE Total [2 weeks in Activity 1; 3 weeks activity 4]																		
Professional & Admin: Anvar Gilmanov 65,654 salary, $22,060 fringe (33.6% fringe rate) 1 FTE Total [Activity 4]																		
Post Doctoral Fellow: Dan Zielinski $90,900 salary, $19,862 fringe (20.75% fringe rate) 1.5 FTE Total [Activity 1]																		
Professional and Admin: Research Fellow: Clark Dennis $48,000 x 2.25yr $49,000 salary, $17,150 fringe (20.75% fringe rate) 2.25 FTE Total [Activity 3]																		
Civil Service- $43,000 salary, $15,050 fringe (27.4% fringe rate) 1.0 FTE Total [Activity 3]																		
Graduate Student: $35,000 salary, $36,000 (37% tuition, 9% fringe rate) 1.0 FTE Total [2 yrs Activity 3]																		
Undergraduate Student: $24,000 9,500 salary, $0 fringe (0% fringe rate) 0.25 FTE Total [10h/wk x 100wk x $12/h) Activity 3]																		
Undergraduate Student: $2000 salary, $140 fringe (7% fringe rate) 0.1 FTE total [Activity 4]																		
Temp casual- $2,785 salary, $215 fringe (7% fringe rate) 0.10 FTE total																		
Professional/Technical Services and Contracts - Total	$268	$268	$0	$150,000	$150,000	$0	$46,725	$46,725	$41,944	$4,781	$5,864	$5,864	$5,864	$0	$202,857	$202,857	$198,076	$4,781
Services- office & gen oper. (printing/duplication, shipping, etc.)			$0			$0	$2,359	$2,359	$2,359	$0	$84	$84	$84	$0	$2,443	$2,443	$2,443	$0
Services- lab & medical (Super-computing Intsitute (MSI) Resources), statistics clinic	$0	$0	$0			$0	$0	$0		$0	$780	$780	$780	$0	$780	$780	$780	$0
Professional Services & contracts- Activity 2: (US Army Corps of Engineers, Swimming performance tests of adult Asian carp at Engineer Research and Development Center in Vicksburg, MS (Activity #2): Jan Hoover (Research Fisheries Biologist). Cost includes: Personnel (91%), Travel to field site (5%), Misc. equip. for swim tunnel (4%))			$0	$150,000	$150,000	$0		$0		$0		$0		$0	$150,000	$150,000	$150,000	$0
Professional Services & contracts- Activity 3 and 4 -Contract with Dr. Dan Zielinski (1 day/wk) to contiue to advise us with implementaion of gate modificaiton software and design of aaccoustic detterent experiments							$10,000	$10,000	$8,000	$2,000	$5,000	$5,000	$5,000	$0	$15,000	$15,000	$13,000	$2,000
Professional Services & contracts- Activity 3: Smith Root Inc Pilot hydrogun test and predesign report (Senior biologist and travel)			$0			$0	$16,000	$16,000	$16,000	$0		$0		$0	$16,000	$16,000	$16,000	$0
Professional Services and contracts- Activity 3: Fish Guidantce Systems Ltd to assist with and advise on tests of air curtains, sounds and lights (likely with their equipment)			$0			$0	$14,031	$14,031	$14,031	$0		$0		$0	$14,031	$14,031	$14,031	$0
Professional Services & contracts- Activity 3: Smith-Root water gun and boomer plate tests with report (6 wk equipment, supplies, biologist, technician; or UofMn Hydro)			$0			$0	$0	$0		$0		$0		$0	$0	$0	$0	$0
Repairs- lab & field ACTIVITY 1: (speaker repair), ACTIVITY 3: various repair	$268	$268	$0			$0	$4,335	$4,335	$1,554	$2,781		$0		$0	$4,603	$4,603	$1,822	$2,781
Equipment/Tools/Supplies - Total	$1,479	$1,479	$0	$0	$0	$0	$107,062	$107,062	$82,462	$24,599	$3,000	$3,000	$2,000	$1,000	$111,541	$111,541	$85,941	$25,599
Supplies- office & gen oper. (Software - Act #1 and #4 modeling, misc. office supplies, Act #3 notebooks, CDs, printer supplies for data	$0	$0	$0			$0	$1,000	$1,000	$588	$412	$1,000	$1,000	$0	$1,000	$2,000	$2,000	$588	$1,412
Supplies- lab & field ACTIVITY 3: (fish for lab and field experiments; fish holding supplies (food, nets, filters, etc); fish behavior supplies (cameras, recording devices); 2 x 200ft of 14/3 SO Cable for transducers; 2 Pontoon floats and supplies ($1000 ea)- for transducers; 150 radiotags (ATS F1835C - could also be accoustic)- fish radio tracking @$164.70; 1 receiver case (ATS)- fish radio tracking; AC-DC power supply (ATS)- fish radio tracking; coaxial cable for antennas-fish radio tracking; surgical supplies for implanting tags (sutures, scalpels, anethestec); boat gas; pipes for blowers; misc field supplies; misc lab supplies) fish food, tarps, materials to build experimental set up, ropes, buoys, shed for blowers ($1,000 ea) boat gas; pipes for blowers; 200 acoustic tags @ $230; additional fish for lab, Activity #4 additional fish.			$0			$0	$84,273	$84,273	$73,620	$10,652		$0		$0	$84,273	$84,273	$73,620	$10,652
Equipment- non capital lab & field ACTIVITY 1: (Computer (high powered desktop)-modeling)	$1,479	$1,479	$0					$0				$0		$0	$1,479	$1,479	$1,479	$0
Equipment- non capital lab & field ACTIVITY 3: 11x Ant switchbox (x11) (14219 ATS)- fish radio tracking, 2 divider nets (12 x 60ft), Laptop Computer - for data collection, 2 CDi2000 amplifiers to drive transducers - implimentation, C75 Hydrophone and calibration- accoustical measurement for transducers), gate for lock, bubble curtain frame, dvr, camera, monitors for lab studies, water pumps for lab assays, hydrophone, accelerometer; ACTIVITY 4: computer for dam calculations			$0			$0	$21,789	$21,789	$8,254	$13,535	$2,000	$2,000	$2,000	$0	$23,789	$23,789	$10,254	$13,535
Capital Expenditures Over $5,000 - Total	$0	$0	$0	$0	$0	$0	$42,950	$42,950	$42,950	$0	$0	$0	$0	$0	$42,950	$42,950	$42,950	$0
Cap expenditures over $5,000: ACTIVITY 3: 2 LL1424HP under water transducers ($8200 ea) - implimentation, 3 Coded receiver datalogger- fish radio tracking ($5800ea); Kraken cabled system; FPZ K12-TD-GOR-50 Blower and attachments;			$0			$0	$42,950	$42,950	$42,950	$0		$0		$0	$42,950	$42,950	$42,950	$0
Other	$66	$66	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$66	$66	$66	$0
Research-specific utilities (when needed at a ROC e.g. for a research pond; specifics required for LCCMR approval); ACTIVITY 1 (electricity to power transducers at Lock & Dam #8 (approx. cost 2 of 3 years), charge for phone line for alarm)	$66	$66	$0			$0	$0	$0		$0		$0		$0	$66	$66	$66	$0
Travel - Total	$4,141	$4,141	$0	$1,075	$1,075	$0	$13,146	$13,146	$9,055	$4,091	$4,014	$4,014	$3,114	$900	$22,376	$22,376	$17,385	$4,991
Travel - MN ACTIVITY 1: (8 trips (LD 8) x 350 miles/trip x 0.56/mi); Lodging (200/person/wk x 2days);Conference (Travel and Lodging) for researcher to formally present research findings and gather information on new advances in the field)	$1,641	$1,641	$0			$0		$0		$0		$0		$0	$1,641	$1,641	$1,641	$0
Travel - MN ACTIVITY 3: 38 wks x 100miles/wk x 0.56/mi), Conference Travel and Lodging (x2); field work travel to/from locks (truck rental, insurance, and gas)			$0			$0	$4,334	$4,334	$3,663	$671		$0		$0	$4,334	$4,334	$3,663	$671
Travel - MN ACTIVITY Scientific Conference for researcher to formally present project findings for researcher to formally present research			$0			$0		$0		$0	$1,000	$1,000	$100	$900	$1,000	$1,000	$100	$900
Travel - Domestic ACTIVITY 1 Scientific Conference for researcher to formally present project findings for researcher to formally present research findings and gather information on new advances in the field (Travel and Lodging)	$2,500	$2,500	$0			$0		$0		$0				$0	$2,500	$2,500	$2,500	$0
Travel - Domestic ACTIVITY 2 (Airfare to Vicksburg, MS (2 x 600), Travel in Vicksburg, MS (a car x 1 wks), Lodging (1000/person/wk x 4 days))			$0	$1,075	$1,075	$0		$0		$0		$0		$0	$1,075	$1,075	$1,075	$0
Travel - Domestic ACTIVITY 3 Scientific Conference for researcher to formally present project findings for researcher to formally present research findings and gather information on new advances in the field and travel and lodging for consultants working with us on accoustic modificaitions and gates to visit the University (Dr. Dan Zielinski, Fish Guidance Systems)			$0			$0	$8,812	$8,812	$5,392	$3,420		$0		$0	$8,812	$8,812	$5,392	$3,420
Travel - Domestic ACTIVITY 4 Scientific Conference for researcher to formally present project findings for researcher to formally present research findings and gather information on new advances in the field (Travel and Lodging)			$0			$0		$0		$0	$3,014	$3,014	$3,014	$0	$3,014	$3,014	$3,014	$0
COLUMN TOTAL	**$134,050**	**$134,049**	**$1**	**$151,075**	**$151,075**	**$0**	**$434,923**	**$434,923**	**$400,934**	**$33,988.6**	**$133,951**	**$133,951**	**$130,058.5**	**$3,892.5**	**$853,999**	**$853,999**	**$816,116**	**$37,882**
		freed up	$0		freed up	$0			freed up	$0			freed up	$0			freed up	$0

Name- Professor: Peter Sorensen 2 weeks $6600 (80.17%Salary, 19.83% benefits, 0.04 FTE	3.636364	
Name- Professor: Vaughan Voller 4 weeks * 1 yr $12,000 (80.17%Salary, 19.83% benefits, 0.08 FTE		**Source of Funds**
Name- Professional & Admin: $ + $65,654 x 1 yr ((66.4 %Salary, 33.6% benefits, 1 FTE)		
Name- Research Assistant Professor: $Salary; (66.4% salary, 33.6% benefits), X% FTE		**Non-state**
Name- Post Doctoral Fellow: Dan Zielinski $60,600 x. 1.5 yr; (79.25 % salary, 20.75% benefits) 1.5 FTE		US Army Corps of Engineers

Name- Post Doctoral Fellow: $43,000 x 2.17yr (79.25% salary, 20.75% benefits) 2.167 FTE	Smith Root Inc
Name- Graduate Student: $Salary; (37% tuition, 54% salary, 9% benefits) 0.5 FTE	ATS
Name- Undergraduate Student: $2000 (93% salary, 7% benefits) 0.09 FTE	**State**

Name- Undergraduate Student: $15,360 (20h/wk x 64 wk x $12/h) (93% salary, 7% benefits) 0.62 FTE	2012 ENRTF
Name- Undergraduate Student: $1000 (93% salary, 7% benefits) 0.05 FTE	
Name- Title (Civil Service): $Salary; (X% salary, 36.8% benefits) XX% FTE	**Private**
	TOTAL OTHER FUNDS:

$ Amount Proposed	$ Amount Spent	Use of Other Funds
$10,900	$10,900	For preliminary tests of Bigheaded carps swimming ability using the USACE swim tunnel in Vicksburg, MS, in Fall 2013

$250,000	$0	In kind support including technician and equipment use (dollar value is an estimate and will not be tracked in this workplan)
$80,000	$0	In kind support including technician and equipment use (dollar value is an estimate and will not be tracked in this workplan)

$69,700		For expedited purchase and installation of transducers at L&D #8
$5,300	$	For expedited purchase and installation of transducers at L&D #8
$415,900	**$10,900**	

Activity 1							
Salaries	**Current Base Salary**	**Yr 1 Base Salary**	**% effort**	Year 1	Year 2	Year 3	Total
Peter Sorensen Professor: 1 week		$3.300	100%	$3 300		$0	$3 300
Vaughan Voller Professor: 2 weeks		$12.000	100%	$12 000		$0	$12 000
Name- Research Assistant Professor: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Professional & Admin: $Salary, XX FTE		$0		$0	$0	$0	$0
Dan Zielinski Post Doc: $Salary; 1 FTE 1.5 years		$60 000	100%	$60 000	$30 750		$90 750
Name- Graduate Student-Academic Yr: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Graduate Student-Summer: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Undergraduate Student: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Title (Civil Service): $Salary: XX FTE		$0		$0	$0	$0	$0
Fringe							
Professor- fringe 19.83% (summer salary)				$654	$0	$0	$654
Professor- fringe 19.83% (summer salary)				$2,380	$0	$0	$2,380
RAP- fringe 33.6%				$0	$0	$0	$0
P&A- fringe 33.6%				$0	$0	$0	$0
Post Doc- fringe 20.75%				$12 450	$6 381	$0	$18 831
Graduate Student- fringe 108.5%				$0	$0	$0	$0
Graduate Student Summer- fringe 23.1%				$0	$0	$0	$0
Undergrad Assistant- fringe 7.4%				$0	$0	$0	$0
Civil Service- fringe 36.8%				$0	$0	$0	$0
Total combined salary and fringe (enter this number in Row 14 on subproject budget tab)							**$127,915**

Activity 2							
Salaries	**Current Base Salary**	**Yr 1 Base Salary**	**% effort**	Year 1	Year 2	Year 3	Total
Peter Sorensen: $Salary: 1 week		$3.300		$0	$3 383		$3 383
Name- Professor: $Salary: XX% FTE		$0		$0	$0	$0	$0
Name- Research Assistant Professor: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Professional & Admin: $Salary, XX FTE		$0		$0	$0	$0	$0
Name- Post Doctoral Fellow: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Graduate Student-Academic Yr: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Graduate Student-Summer: $Salary: XX FTE							
Name- Undergraduate Student: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Title (Civil Service): $Salary; XX FTE		$0		$0	$0	$0	$0
Fringe							
Professor- fringe 19.83% (summer salary)				$0	$671	$0	$671
Professor- fringe 19.83% (summer salary)				$0	$0	$0	$0
RAP- fringe 33.6%				$0	$0	$0	$0
P&A- fringe 33.6%				$0	$0	$0	$0
Post Doc- fringe 20.75%				$0	$0	$0	$0
Graduate Student- fringe 108.5%				$0	$0	$0	$0
Graduate Student Summer- fringe 23.1%				$0	$0	$0	$0
Undergrad Assistant- fringe 7.4%				$0	$0	$0	$0
Civil Service- fringe 36.8%				$0	$0	$0	$0
							$4,053

Activity 3- updated 11/6/15							
Salaries	**Current Base Salary**	**Yr 2 Base Salary**	**% effort**	Year 1= feb 14- Sept 15	Year 2 Sept 15- Sept 16	Year 3 Oct 2016- June 17	Total
Name- Peter Sorensen $Salary; 4 weeks		$3.200		$3 200	$9 600	$6 724	$19 524
Name- Professor: $Salary: XX% FTE		$0		$0	$0	$0	$0
Name- P/A Junior Scientist Professor: $Salary: XX FTE		$41.000		$41.000		$0	$41.000
Name- Professional & Admin: $Salary, XX FTE		$41		$0	$0	$0	$0
Name- Post Doctoral Fellow: $Salary: XX FTE		$0		$0	$0	$0	$0
Name- Graduate Student-Whole Yr: $Salary: XX FTE		$0		$0	$21.000	$21.525	$42.525
Name- Graduate Student-Summer: $Salary: XX FTE							$0
Name- Undergraduate Student: $Salary: XX FTE				$24,000	$14,304		$38,304
Dan Krause- Title (Civil Service): $Salary: XX FTE		$34.000	33%	$11.322	$11.605	$11.895	$34.822
Fringe							
Professor- fringe 33.7				$1.078	$3.235	$2.266	$6.580
Professor- fringe 33.7				$0	$0	$0	$0
P&A Jr Scientist- fringe 33.7%				$13.817	$0	$0	$13.817
P&A- fringe 33.7%				$0	$0	$0	$0
Post Doc- fringe 22.4%				$0	$0	$0	$0
Graduate Student- whole year fringe 85.281%				$0	$17,909	$18,357	$36,266
Graduate Student Summer- fringe 23.1%				$0	$0	$0	$0
Undergrad Assistant- fringe 0%				$0	$0	$0	$0
Civil Service- fringe 27.4%				$3 102	$3 180	$3 259	$9 541
							$242,379

Activity 4								TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL		
Salaries	**Current Base Salary**	**Yr 1 Base Salary**	**% effort**	Year 1	Year 2	Year 3	Total	Budget	Revised Budget	Amount Spent	Balance	Projected	Projected Surplus/ (deficit)		
Name- Professor: $Salary: XX% FTE		$0		$0	$0	$0	$0	$26 207							
Name- Professor: $Salary: XX% FTE		$0		$0	$0	$0	$0	$12.000						$38.207	#######
Name- Research Assistant Professor: $Salary: XX FTE		$0		$0	$0	$0	$0	$41.000							
Dan Zielinski, Research Associate Professional & Admin: $, XX FTE		$60.000	100%			$63.038	$63.038	$63.038							
Name- Post Doctoral Fellow: $Salary: XX FTE		$0		$0	$0	$0	$0	$90.750							
Name- Graduate Student-Academic Yr: $Salary: XX FTE		$0		$0	$0	$0	$0	$42.525							
Name- Graduate Student-Summer: $Salary: XX FTE								$0							
Name- Undergraduate Student: $Salary: XX FTE		$0		$0	$0	$2.000	$2.000	$40.304							
Name- Title (Civil Service): $Salary; XX FTE		$0		$0	$0	$0	$0	$34.822						##########	
								$0							
Fringe								$0							
Professor- fringe 19.83% (summer salary)				$0	$0	$0	$0	$7,905							
Professor- fringe 19.83% (summer salary)				$0	$0	$0	$0	$2,380						$10,284	
RAP- fringe 33.6%				$0	$0	$0	$0	$13.817							
P&A- fringe 33.6%				$0	$0	$21.181	$21.181	$21.181							
Post Doc- fringe 20.75%				$0	$0	$0	$0	$18.831							
Graduate Student- fringe108.5%				$0	$0	$0	$0	$36.266							
Graduate Student Summer- fringe 23.1%				$0	$0	$0	$0	$0							
Undergrad Assistant- fringe 7.4%				$0	$0	$148	$148	$148							
Civil Service- fringe 36.8%				$0	$0	$0	$0	$9 541							
								$0							
							$86,366	########							

90000

17909
0.85281

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	***Activity 3: Test and Develop New Acoustical Deterrent Systems for Locks***			
BUDGET ITEM	**Activity 3 Budget**	**Activity 3 Revised Budget**	**Amount Spent**	**Activity 3 Balance**
Personnel (Wages and Benefits) - Total (Estimates)	~~$190,773~~	$235,945	$85,454	$150,491
Professor: Peter Sorensen $21,800 salary, $7,399 fringe (33.7 % fringe rate) 0.12 FTE Total [8 weeks total: 1 wk Activity 1, 1 wk Activity 2, 4 6 wks Activity 3,]	$12,400	$18,700		
	$2,455	$6,545		
Professor: Vaughan Voller $15,100 salary, $3,234 fringe (33.7% fringe rate) 0.08 FTE Total [2 weeks in Activity 1]		$0		
		$0		
Professional & Admin: Zielinksi $65,654 salary, $22,060 fringe (33.6% fringe rate) 1 FTE Total [Activity 4]		$0		
		$0		
Post Doctoral Fellow: Dan Zielinski $90,900 salary, $19,862 fringe (20.75% fringe rate) 1.5 FTE Total [Activity 1]		$0		
		$0		
Professional and Admin: Research Fellow $~~48,000 x 2.25yr $~~49,000 salary, $17,150 fringe (20.75% fringe rate) 2.25 FTE Total [Activity 3] Clark	$110,170	$49,000		
	$40,068	$17,150		
Civil Service- $43,000 salary, $15,050 fringe (27.4% fringe rate) 1.0 FTE Total [Activity 3]	$0	$43,000		
	$0	$15,050		
Temp casual- $2,785 salary, $215 fringe (7% fringe rate) X FTE total	$2,785	$2,785		
bene- 7%	$215	$215		
Graduate Student: $35,000 salary, $36,000 (37% tuition, 9% fringe rate) 1.0 FTE Total [2 yrs Activity 3]		$35,000		
		$39,000		
Undergraduate Student: $~~24,000~~ 9,500 salary, $0 fringe (0% fringe rate) 0.25 FTE Total [10h/wk x 100wk x $12/h) Activity 3]	$21,000	$9,500		
	$1,680	$0		
Undergraduate Student: $2000 salary, $140 fringe (7% fringe rate) 0.1 FTE total [Activity 4]		$0		

		$0		
Columns sum down	190773	$235,945	0	0
		$232,945		
139.25				

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MANAGEMENT BRIEF

Bubble Curtain Deflection Screen Diverts the Movement of both Asian and Common Carp

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Abstract
Bubble curtains are a relatively simple type of behavioral deterrent that produces acoustic and hydrodynamic fields that could serve as a management tool to reduce movement of Asian carp species in many locations. In a proof-of-concept laboratory study, we tested whether two Asian carp species, the Silver Carp *Hypopthalmichthys molitrix* and the Bighead Carp *H. nobilis*, will avoid bubble curtains, and to the same extent as the Common Carp *Cyprinus carpio*, which has a similarly specialized hearing system. We explored the theory and application of a bubble curtain deflection screen using a split-passage experimental channel equipped with angled bubble curtains while mapping both pressure and particle motion (sound) fields. The bubble curtain reduced passage of all three species through the experimental channel by 73–80% while producing sound between 100 and 1000 Hz at 145 dB, well within the hearing range of all three carp. While Common Carp were diverted to an unblocked channel, the Asian carp species reduced overall swimming activity, suggesting a slightly greater overall sensitivity. These results suggest bubble curtains could serve as viable and inexpensive deterrent systems to inhibit the movement of both Asian carp and Common Carp into shallow waters while having minimal impacts on other fish.

Since their introduction in the 1970s, two species of Asian carp species, the Silver Carp *Hypopthalmicthys molitrix* and the Bighead Carp *H. nobilis*, have become established in the Mississippi River as far north as Pool 18 near Burlington, Iowa, (USFWS 2014) and in the Illinois River as far north as Dresden Island Pool near Morris, Illinois. If left unchecked, these fish could invade farther upstream and adversely impact aquatic food webs, native populations, recreational opportunities, and consequently, commercial and recreational fisheries (Schrank et al. 2003; Irons et al. 2007; Sampson et al. 2009; Sass et al. 2014). The National Asian Carp Management Plan has identified a need to develop technologies to control the expansion of carp (ACRCC 2014). Tens of millions of dollars have already been spent in the Chicago Area Waterway System (which is part of the Illinois Waterway System) to install and operate the Electric Dispersal Barrier with the goal of blocking all aquatic life from entering or exiting the Great Lakes (Moy et al. 2011). This barrier is located in the Chicago Sanitary and Ship Canal, which is a relatively narrow passage (~50 m wide) that was built to divert flow from the Chicago River. Native fish are not a concern at this industrialized site, making an electrical barrier a reasonable option. In contrast, electrical barriers are not a viable option in the upper Mississippi River and its large network of tributaries because of high costs, the risk they can pose to human safety, and their potential to block valuable native fish (Noatch and Suski 2012). Behavioral deterrents that use nonphysical stimuli to influence fish movement are thus being considered as an alternative since they are generally easier and less expensive to deploy, are navigable, and can be taxon-specific (Popper and Carlson 1998; Coutant 2001; FishPro Consulting Engineers and Scientists 2004; Noatch and Suski 2012; Barr Engineering 2013). Acoustic deterrents appear to have particular promise because they are safe and Asian carp, as well as the Common Carp *Cyprinus carpio*, have specialized hearing abilities (Popper 1972; Lovell et al. 2006). Sound has already been successfully field tested for Common Carp (Zielinski and Sorensen 2015).

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Among the sound production technologies available are underwater speakers (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012; Vetter et al. 2015), water-guns (Romine et al. 2015), and bubble curtains, which use pressurized air-bubbles to create both acoustic and hydrodynamic stimuli. Bubble curtains have special promise by themselves to serve as a practical control for Asian carp in small tributaries and channels (e.g., lock chambers). This is so because bubble curtains are inexpensive to install and maintain (they can be easily laid on the river bottom unlike speakers), are safe, and produce a broad spectrum of sound (Zielinski et al. 2014). We have already shown that bubble curtains alone are an effective deterrent for Common Carp (Zielinski et al. 2014; Zielinski and Sorensen 2015). In particular, we found that when air flow and bubble size are optimized for sound production, bubble curtains can reduce passage of juvenile Common Carp by 75–80% in the laboratory and block up to 60% of downstream swimming juveniles in the field, when used in a cross-stream configuration (i.e., full width barrier placed perpendicular to flow) (Zielinski et al. 2014; Zielinski and Sorensen 2015). In some situations, this level of deterrence will likely be useful for management, especially given its low cost (about US$1,250/m of bubble curtain [see Zielinski and Sorensen 2015]). Our laboratory studies suggest that the sound produced by bubble plumes is primarily responsible for deterring Common Carp passage because the sound produced overlaps the range of sounds this species hears and bubble curtain efficacy is not hindered by low levels of ambient light (Zielinski et al. 2014).

Although all fish detect the particle motion component of sound via their inner ear, Ostariphysians (including the Asian carp species and Common Carp) possess a Weberian apparatus. This anatomical link between the swim bladder and inner ear allows them to detect sound across a wider frequency bandwidth and at lower sound pressures than other fish lacking this specialization (Popper and Fay 2011). Previous studies of Bighead and Silver carp responses to systems that use underwater speakers to project sounds into low volume bubble curtain systems have shown these systems to function as deterrents (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012). However, whether optimized bubble curtains alone, which are simpler and less expensive than speaker driven systems, might be equally effective has not yet been tested. Further, although Asian carp and Common Carp have very similar hearing abilities (Popper 1972; Lovell et al. 2006; Ladich and Fay 2013), suggesting that they may be similarly affected by acoustic deterrents, this possibility has yet to be ascertained. This is an important question because only Common Carp are available for in situ tests in the upper Mississippi River, where Asian carp are still uncommon. Sound is of special interest because the hearing capabilities of fish vary (Popper and Fay 2011) suggesting that sound systems could be relatively taxon-specific. Studies of both Walleye *Sander viterus* and Muskellunge *Esox masquinongy*, fish without hearing specializations, show they are minimally deterred by bubble curtains systems alone or combined with other technologies (Flammang et al. 2014; Stewart et al. 2014).

We tested the hypothesis that Silver Carp, Bighead Carp, and Common Carp avoid a bubble-curtain deterrent system in the laboratory as a proof-of-concept study to guide future field tests and application. A split-passage experimental channel was used to test the effectiveness of a bubble-curtain system as a deflection behavioral deterrent. These results were then compared with cross-stream designs tested by Zielinski et al. (2014) and Zielinski and Sorensen (2015) for the Common Carp. Our study appears to represent the first attempt to quantify avoidance behavior of Asian carp to a deterrent system comprised solely of an air-bubble curtain. Both sound pressure and acoustic particle motion fields produced by the bubble curtain were measured to permit future study and improvement. Potential field applications are addressed.

METHODS

Experimental animals.—Juvenile Silver Carp (mean mass = 120 g, SD = 41; mean = 237 mm TL, SD = 35) and Bighead Carp (mean = 215 g, SD = 103; mean = 280 mm TL, SD = 44) were obtained from the Columbia Environmental Research Center (U. S. Geological Survey, Columbia, Missouri) and held in circular 100-L tanks. Silver and Bighead carp were fed a planktonic diet consisting primarily of spirulina and chlorella algae (see Hansen et al. 2014) once a day between 1000 and 1400 hours. Common Carp (mean = 416 g, SD = 113; mean = 298 mm TL, SD = 25) were caught in Casey Lake, Minnesota by pulsed DC electrofishing in July 2012 and transported to the laboratory, where they were maintained in tanks (1.5-m diameter, 50 cm deep). Common Carp were fed pellets (Silver Cup, Utah) once a day between 1000 and 1400 hours and matured while in captivity; the Asian carp did not. We attempted to match fish size irrespective of maturity, which is not known to influence responsiveness to sound. All holding and experimental tanks were supplied with flow-through 20°C well water.

Passive integrated transponder (PIT) tags (12.0 × 2.12 mm, half-duplex, OregonRFID, Oregon) were implanted into seven Common Carp, seven Silver Carp, and three Bighead Carp. Before tagging, all carp were anesthetized in a 0.05% solution of buffered tricaine methanesulfonate (MS-222, Western Chemicals, Utah), and a 1.4-mm diameter syringe fitted with a 12-gauge hypodermic needle was used to inject a PIT tag into each carp's body cavity between their pelvic and pectoral fins. Punctures were allowed to heal for 4 weeks (Acolas et al. 2007) prior to the start of experiments. Tagging resulted in no mortality. The remaining 14 Common Carp, 14 Silver Carp, and 6 Bighead Carp were left untreated and used with marked carp. All experimental procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1201A08922), and all necessary federal and state permits for shipping and holding prohibited species were obtained.

Experimental set-up.—Experiments were performed in a cylindrical tank (3-m diameter) with an insert (1-m diameter) and wall (2 × 0.5 m) which created a split-passage circular channel with a nominal width of 0.5 m and water depth of 25 cm (Figure 1). Water was supplied to the tank through a submerged pipe located in the single channel portion of the tank and produced a 5 cm/s current. Two bubble curtains were placed in the tank and each was positioned diagonally across the openings of the outside channel while the inner channel was left as control to test for diversion. Fish were tested in groups of three (two untagged, one tagged) to allow them to form shoals because these carp are social and behave more naturally when tested as groups (Sisler and Sorensen 2008; Huntingford et al. 2010; Sloan et al. 2013; R. Ghosal and P. W. Sorensen, University of Minnesota, unpublished results). Only one PIT-tagged fish was used at a time because the PIT antennas could only detect one tag at a time, and Zielinski et al. (2014) found that the movement of a single Common Carp reliably describes that of the entire shoal. Passage data were reported for the tagged fish only.

Fish movement was tracked using a PIT antenna array using the Oregon RFID Multi-Antenna HDX reader with four antennas tuned to an inductance of about 60–80 μH. The system was configured for a 10-Hz sampling frequency at each antenna. Each time a tagged fish passed through an antenna, the time of passage, PIT identification number, antenna number, and time between detections were logged onto a memory card for analysis. Antennas were positioned to differentiate between movement through the inside and outside channels, as well as overall activity (Figure 1). Antenna numbers 1, 2, and 4 were placed in the single channel portion of the tank, while antenna 3 was placed midchannel of the outside channel. Antenna 3 was manually tested using PIT tags that were pulsed through at various speeds prior to each trial to ensure that only tagged fish in the outside channel were detected. Manual testing indicated a detection probability at each antenna of >99%.

The bubble curtain was created with a 3.8-cm diameter PVC pipe built in a U-shape configuration with a 15-cm spacing between each leg and 3-mm diameter holes spaced every 5 cm. The same design was used in cross-stream field tests (Zielinski et al. 2014). To create the bubble curtain, a S41 regenerative air-blower (Pentair Aquatic Ecosystems, Florida) was used at 5 kPa to supply 12 L/s of air thorough 1 m of water. This air flow was one-ninth of what our previous studies found to be necessary to drive the highest levels of deterrence in Common Carp in the laboratory (Zielinski et al. 2014). We wanted to test lower airflows both to compare efficacies and because air production can be a challenge in deep water (Noatch and Suski 2012). The blower was operated using an automated switch that was programmed to turn the blowers on or off after a designated period.

Trials were conducted between 2000 and 0600 hours with all lights off in our testing facility and a black tarp covering the experimental tanks so that no light was visible, minimizing the role of any visual stimulus. For each trial, carp were placed into the circular channel and allowed to acclimate for 10 min before the trial began. Each 7 h trial began with a 3.5 h control period, in which the bubble curtain was in place but no bubbles were produced and carp were able to swim through both channels. This control period was followed by a 3.5 h test period when the bubble curtains in front of the outside channel were turned on (irrespective of where carp were located). Seven replicates were performed for Common Carp and Silver Carp and three for Bigheaded Carp because we had few of these in the same size range.

Swimming behavior near the bubble curtain (<20 cm) was also monitored using an underwater camera with infrared LEDs in three additional trials to help us understand the specific role of sound fields, which were also mapped (see below). The camera was located on the tank bottom and positioned to capture movement near antenna 1 to document behavior in the outside channel. Qualitative descriptions of swimming behaviors including channel location, position within channel, turning behavior, freezing, and direction of movement were used to compare how each species reacted with the bubble curtain. The closest distance each carp came to the bubble curtain without crossing it was also recorded.

Bubble curtain sound field.—Sound pressure levels (SPL) and acoustic particle acceleration was mapped at a depth of 12.5 cm below the water surface at 10-cm intervals in the quadrant of the bubble curtains and at 25-cm intervals in the remaining space. This appears to be the first time acoustic particle motion measurements have been taken around a bubble curtain system. Acoustic measurements were made using a PVC probe similar to that used by Zeddies et al. (2012), which contained a hydrophone and triaxial accelerometer. Pressure measurements were obtained using a C55 hydrophone (Cetacean Research, Washington) with integral power amplifier, which has a usable frequency range of 0.008–100 kHz and a sensitivity of approximately –163.5 dB referenced at (ref) 1 V/μPa. The signal was sampled at 44.1 kHz and fed through a TASCAM US-122mkII (TASCAM, California) audio interface, digitized, and stored on a Windows-based computer. Acoustic particle acceleration measurements were also obtained using a PCB model W356A12 triaxial accelerometer (PCB Piezoelectronics, New York), which was made neutrally buoyant by embedding it in a foam enclosure. The accelerometer had a usable frequency of 0.5–5,000 Hz and sensitivity of approximately 100 mV/ms^{-2}. The signal was conditioned using a PCB 482C05 conditioner and fed through a USB-1208FS-Plus data acquisition board (Measurement Computing, Massachusetts) sampling each channel at 16 kHz. At each location a 5 s sample was split into 10 signal ensembles and averaged to improve the signal-to-noise ratio. Data acquisition hardware was controlled by a

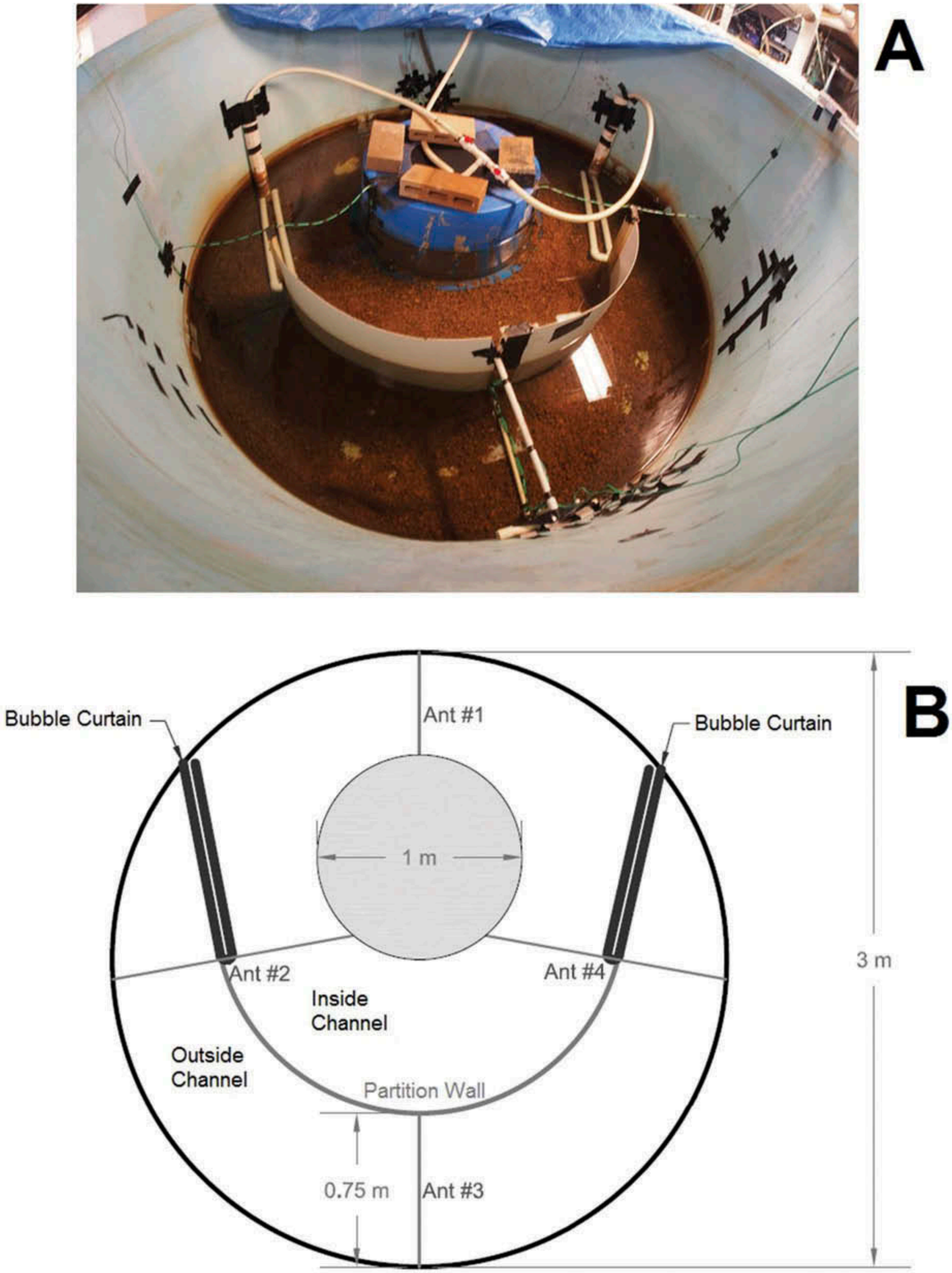

FIGURE 1. **(A)** Top view of the experimental bubble curtain tank. Bubble curtains (90 cm long white PVC pipes) are located at the end of the 50-cm-high partition wall. Water depth was 25 cm. **(B)** Overhead schematic of split-path circular channel showing position of bubble curtains and PIT antennas. Antenna number 3 was tuned and positioned to only detect movement through the outside channel.

custom graphical user interface operating in Matlab (Mathworks, Massachusetts), which also was used to analyze and transform the pressure and particle acceleration waveforms into the frequency domain.

Statistical analysis.—Movement data were analyzed in several ways. First, a nonparametric chi-square (χ^2) test was used to evaluate deflection, i.e. whether the relative number of tagged carp passing through the inside and outside channels changed when the bubble curtain was turned on. The total number of passages through each channel during the control period was used as the expected count. We did not monitor differences in direction of carp passage because there was little flow (the bubble curtain produced water velocities >15 cm/s, a value that greatly exceeded the 5-cm/s background flow during the control periods). Second, any change in passage through the outside channel as a result of bubble curtain operation was calculated:

$$\%\text{Reduction} = \left(\frac{N_{\exp ected} - N_{observed}}{N_{\exp ected}}\right) \cdot 100\%,$$

where $N_{\exp ected}$ is the mean number of passages through the outside channel during controls and $N_{observed}$ is the mean number of passages through the outside channel during treatments. Third, the total activity of each species before and during bubble curtain operation were quantified by summing the number of times tagged carp passed between any two antennas (i.e., antenna 3 to 4 or antenna 1 to 2) during the control and experimental periods. A Kruskal–Wallis *H*-test with Mann–Whitney pairwise comparisons was then used to determine whether the activity level of each species changed. To evaluate the video data, a Kruskal–Wallis *H*-test was also used to compare the closest distance each species reached without crossing the bubble curtain. All statistical analyses used a significance level of α = 0.05.

RESULTS

Bubble Curtain Deflection Tests

All three species of carp swam through the outside channel twice as often as the inside channel during control periods (no bubbles) (Figure 2) while exhibiting a similar level of activity (Figure 3). The mean ± SE number of passages through the inside and outside channel during controls was 38 ± 6 and 80 ± 14 for Common Carp, 28 ± 5 and 94 ± 10 for Silver Carp, and 20 ± 2 and 110 ± 23 for Bighead Carp (Figure 2). The bubble curtain reduced Common Carp passage through the outside channel by 73% (χ^2 = 316.4, $P < 0.05$). Similarly, Silver Carp passage through the outside channel was reduced by 80% (χ^2 = 128.5, $P < 0.05$) and Bighead Carp passage was reduced by 83% (χ^2 = 107.4, $P < 0.05$). However, while Common Carp swam through the inside control channel twice as often when the bubble curtain was on ($P < 0.05$), the passage rates of the Silver and Bighead carp through the

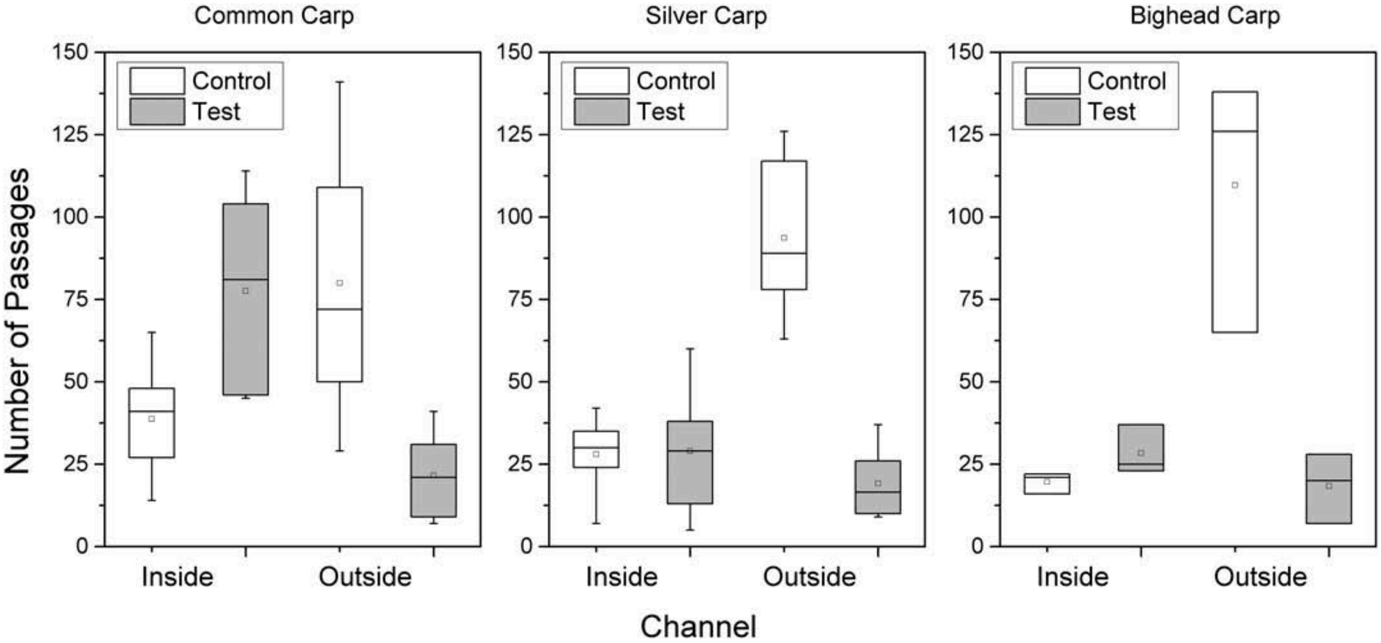

FIGURE 2. Box plots of the number of passages through the inside and outside channel by Common Carp (number tested, $N = 7$), Silver Carp ($N = 7$), and Bighead Carp ($N = 3$), where box = upper and lower quartiles, square = mean, horizontal line = median, and whiskers = 1% and 99% values. Chi-square tests indicated that the reduction in passages through the outside channel was significant for all carp species ($P < 0.05$). The outside channel was blocked by the bubble curtain during test periods.

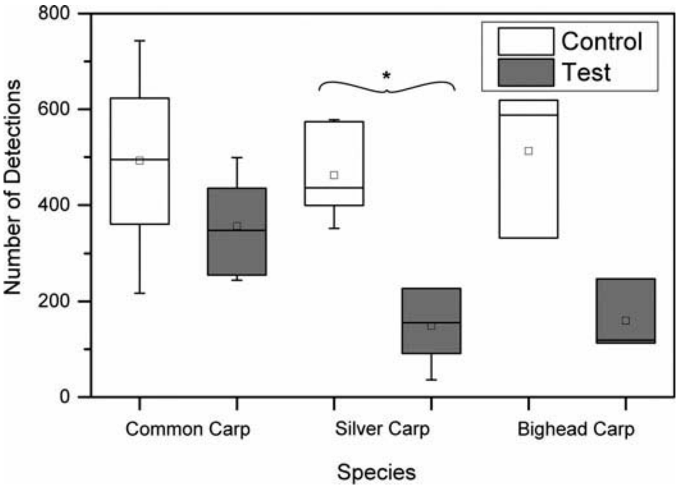

FIGURE 3. Box plots of the number of detections at consecutive antenna as a metric of total activity for three carp species during control and test periods with bubble curtains; see Figure 2 for box plot explanation and sample sizes. Pairs with significant difference are denoted by an asterisk (Kruskal–Wallis with Mann–Whitney pairwise comparisons at α = 0.05.).

inside channel did not change. This change in activity by the Asian carp species was seen in measures of overall activity. Thus, while the total swimming activity of all three carps was the same during control periods (Kruskal–Wallis: $P > 0.05$; Figure 3), total Common Carp activity was unaffected by the bubble curtain (Mann–Whitney: $P > 0.05$); however, Silver Carp activity decreased from 497 ± 126 to 165 ± 81 (Mann–Whitney: $P < 0.01$) and Bighead Carp also decreased from 512 ± 91 to 160 ± 44 (Mann–Whitney: $P > 0.05$, but $N = 3$).

Swimming Behavior Near the Bubble Curtain

All three species typically swam in loose groups along the outside wall of the tank during control periods. Once the bubble curtain was activated, carp swam parallel to the bubble curtain and entered the inside channel rather than cross the bubble curtain. Carp rarely crossed the bubble curtain. The closest distance ± SE to the bubble curtain that individuals of all three species reached before turning around (or occasionally proceeding forward) was 9 cm ± 1 for Common Carp, 10 cm ± 1 for Silver Carp, and 9 cm ± 1 for Bighead Carp (Kruskall–Wallis: $P > 0.5$).

Characteristics of Bubble Curtain Sound Field

The bubble curtain produced a broad spectrum sound with peak frequencies between 100 and 300 Hz and 1,000 Hz (Figure 4A). The frequency range of the bubble curtain sounds overlapped the hearing range of Common Carp (Popper 1972) as well as Silver and Bighead carp (Lovell et al. 2006). Contour plots of the sound pressure field showed the maximum SPLs to be 145 dB ref 1 μPa at 200 Hz and 125 dB ref 1 μPa at 1,000 Hz (Figure 5). The area of peak SPL was located directly above the bubble curtain, acting as an extension of the partition wall. The pressure gradient was oriented perpendicular to the opening between channels. Within 25-cm from the bubble curtain, the SPL decreased to about 15 dB ref 1 μPa above background with 115 dB ref 1 μPa at 200 Hz and 95 dB ref 1 μPa at 1,000 Hz.

The particle acceleration power spectrum peaked in all directions between 100 and 300 Hz (Figure 4B). The contour plot of particle acceleration resembled the SPL contours with a peak of 10 dB ref 1 cm/s^2 above the bubble curtain (Figure 5C). Particle acceleration decreased rapidly away

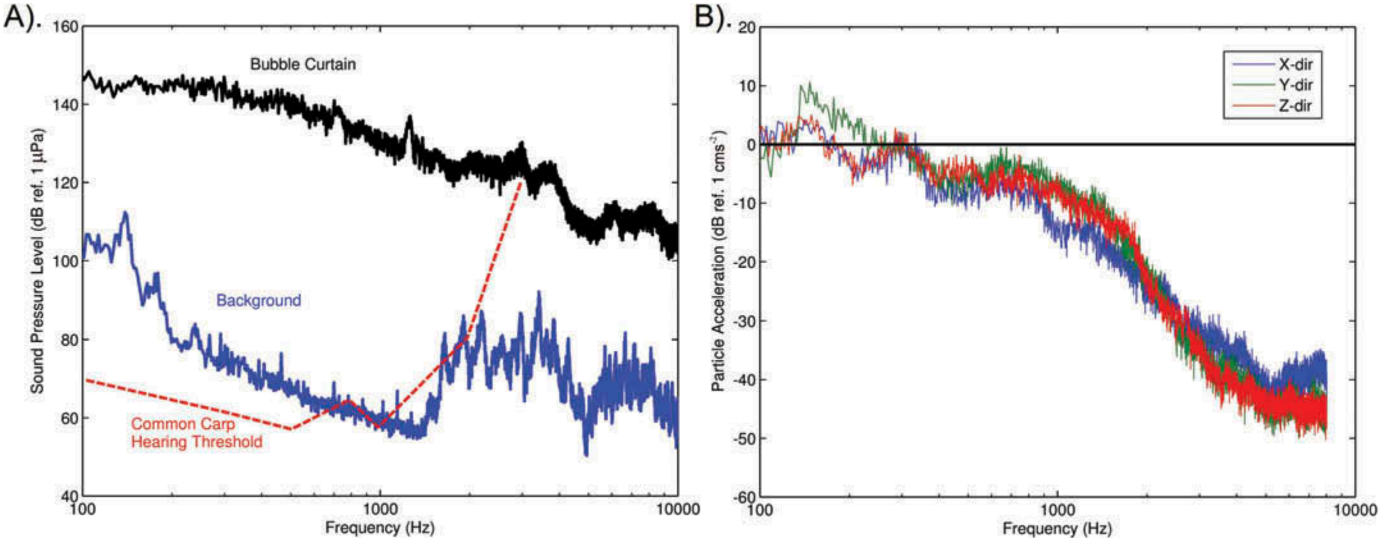

FIGURE 4. **(A)** Sound pressure level power spectrum of the bubble curtain (solid black line), background (solid gray line), and Common Carp hearing threshold (dashed red line; Popper 1972). **(B)** Particle acceleration in each direction: perpendicular (X-dir), parallel (Z-dir), and vertical (Y-dir) to the bubble curtain. Sound measurements were obtained 5 cm away from the bubble curtain in the center of the channel and 12.5 cm from the tank bottom.

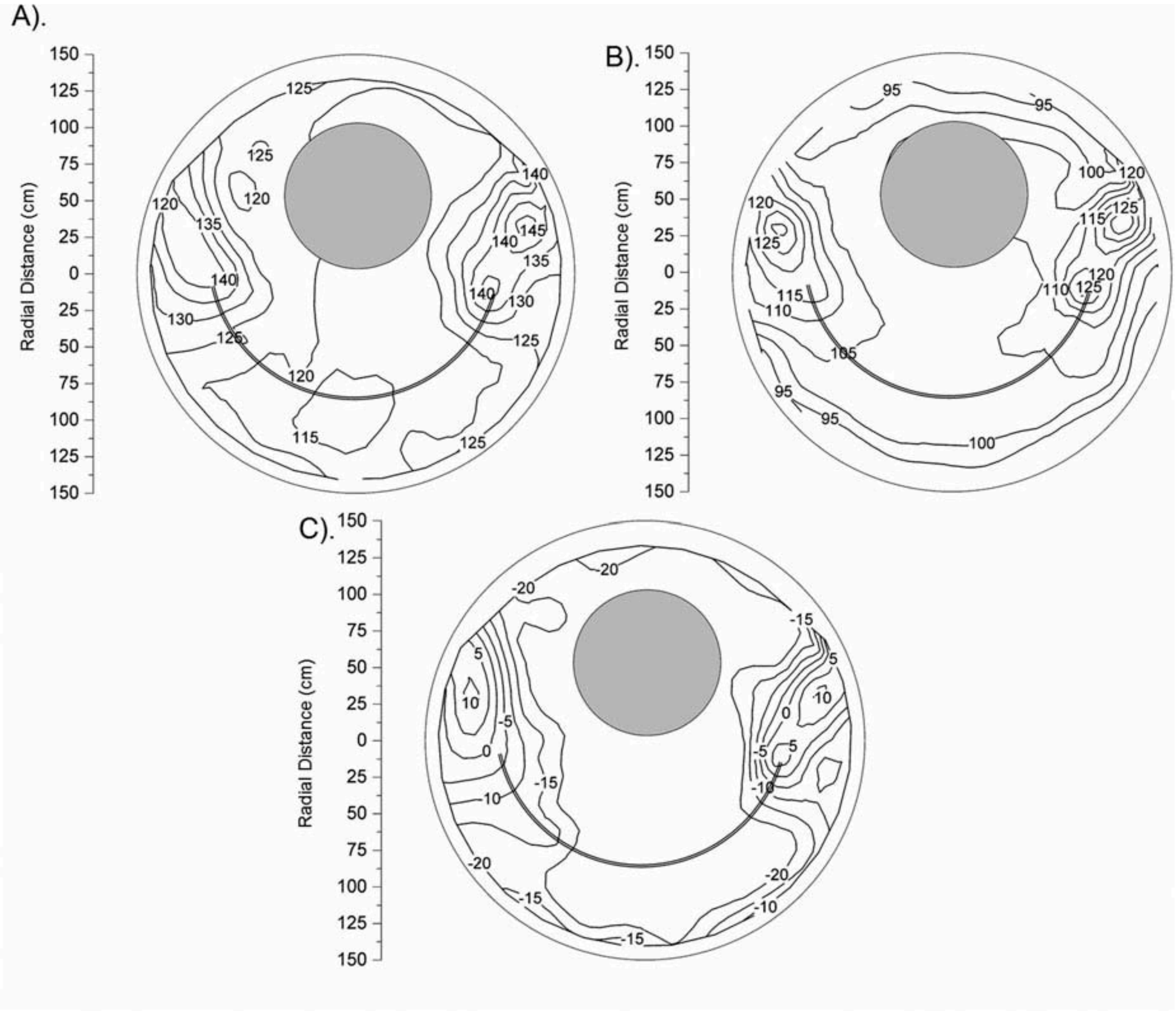

FIGURE 5. Plan view of the sound pressure field in decibels (ref 1μPa) in the experimental tank at a depth of 12.5 cm at **(A)** 200 Hz, **(B)** 1,000 Hz, and **(C)** acoustic particle acceleration in dB (ref 1 cm/s^2). The bubble curtains extended tangentially from the ends of the partition wall (curved line). The background sound pressure level at 200 Hz and 1,000 Hz was 80 and 60 dB ref 1μPa, respectively.

from the bubble curtain, reaching accelerations less than –20 dB ref 1 cm/s^2 at a distance of about 25 cm from the bubble curtain.

DISCUSSION

This study demonstrated that Common Carp, Silver Carp, and Bighead Carp avoid bubble curtains in the laboratory and to similar extents. Functioning as a deflection screen, the bubble curtain diverted passage of all three carp species by 73–83% away from their preferred route in a split passage experimental channel. The remarkably similar effects that the bubble curtain had on all three carp species suggests that the Common Carp is a suitable model to investigate how other carps are deterred by sound and could serve as a reasonable surrogate of Asian carp species when testing the effects of acoustic deterrents in the upper Mississippi where the latter are not yet abundant. These similarities are not surprising given the similar abilities of these three carp species to hear, although their different life history attributes suggest that field tests will eventually be required, especially in shallow tributaries of the upper Mississippi River and its lock chambers. Caution should also be exercised in scaling laboratory data to field scale because the acoustic and hydrodynamic fields produced by bubble curtains will behave differently (Zielinski and Sorensen 2015).

The observed avoidance behaviors of Silver and Bighead carp are in close agreement with previous laboratory and field experiments. Not only have similar rates of deterrence been noted to bubble curtains by Common Carp (Zielinski et al. 2014; Zielinski and Sorensen 2015), but bubble curtains supplemented with underwater speakers have been shown to inhibit the movement of Silver and Bighead carp in hatchery pools and streams (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012). The bubble curtain tested here produced sound pressure levels roughly 30–40 dB ref 1 μPa above background levels and the hearing thresholds of all three carp species in their most sensitive range (100–2,000 Hz). Although carp avoided this bubble curtain, fish without hearing specializations (e.g., Walleye, Muskellunge, Ruffe *Gymnocephalus cernuus*, White Perch *Morone americana*, and Atlantic Salmon *Salmo salar* [smolts]) have been shown to be largely undeterred by these systems (Sager et al. 1987; Welton et al. 1997; Dawson et al. 2006; Flammang et al. 2014; Stewart et al. 2014). These taxon-specific responses support the possibility that bubble curtains can serve as taxon-specific acoustic deterrent for invasive carps, whose hearing specializations make them disproportionately susceptible to noise-induced stress and movement control than species without such specializations (Maes et al. 2004; Smith et al. 2004).

Bubble curtain deflection systems could ultimately be used to guide carp away from critical habitat or passageways either towards traps (Johnson et al. 2014) or toward areas where carp could be harvested more efficiently. Specifically in the upper Mississippi River system bubble curtains could be used at relatively low cost to limit Asian carp access to low-velocity waters, such as tributaries and oxbow lakes, where large numbers of Asian carp in the lower reaches of the Mississippi River have been observed (Varble et al. 2007; Kolar et al. 2007; Wilson 2014). Juvenile Asian carp have reached nearly 60 km upstream into shallow tributaries of the Missouri River (i.e., Louter River, Cedar River, and Silver Creek; D. Chapman, U.S. Geological Survery, personal communication). The Mississippi River lock chambers offer unique opportunities to deploy bubble curtains because they have a well-defined channel, shallow and slow moving water, and already have much of the infrastructure necessary to operate bubble curtains. Even modestly effective systems might be useful when no alternatives are possible and reducing propagule pressure is a goal.

The fundamental difference between the bubble curtain system we tested and commercially available bubble-speaker-strobe light deterrent systems (Taylor et al. 2005; Ruebush et al. 2012) is cost and simplicity because the release of bubbles into the water column can serve as the sole source of sound, at least if designed in the manner we described. In certain situations underwater speakers could be used to supplement or even replace the sound generated by the bubble curtain, but their use may not be straightforward. While Vetter et al. (2015) demonstrated speakers playing complex sounds (derived from boat motors) have greater impact on modulating Silver Carp swimming behaviors than pure tones, Zielinski et al. (2014) showed Common Carp passage was reduced more by a bubble curtain alone than an array of underwater speakers alone playing a recording of the bubble curtain. Furthermore, a deterrent consisting of just an air-source and bubble diffuser has the benefit that it could be constructed, installed, and maintained at relatively low cost and readily repositioned or removed as needed.

In this study we also characterized the acoustic near field of the bubble curtain (i.e., sound source distance less than the signal wavelength/2π) where acoustic particle motion dominates the sound field (Kalmijn 1988) and show that it probably explains deterrence. In particular, the acoustic particle acceleration produced by the bubble curtain we tested exceeded the 0 dB ref 1 cm/s^2 threshold for acoustic particle acceleration that elicits avoidance behaviors (Knudsen et al. 1992) within 25 cm of the bubble curtain; that is approximately the distance where we noted carp to be deflected and where acceleration reached a maximum of 10 dB ref 1 cm/s^2 at frequencies <300 Hz. In contrast, regions of elevated Reynolds shear stress, a hydrodynamic force implicated in disorienting fish (Silva et al. 2012), extended 50–100 cm away from a similarly sized bubble curtain (Zielinski et al. 2014). Although correlative, the extremely limited range of the sound field stimuli (especially particle acceleration) compared with the wider range of hydrodynamic stresses and the close proximity that carp swam to the bubble curtain (10 cm) seems to confirm that sound and particle motion in particular, has a prominent role in detection and avoidance of bubble curtains by carp. This opens the possibility for further research to study enhancing sound fields to direct fish movement.

Although a direct comparison between the bubble curtain deflection screen tested here and the cross-stream bubble curtains tested by Zielinski et al. (2014) is not straightforward because the latter study used a single channel design, our results provide evidence that behavioral deterrents function best as deflection screens. It may be easier to deflect a fish than to block one. This finding is in agreement with the routine use of behavioral deterrents as deflection screens in fish protection systems at hydropower facilities (Coutant 2001; Welton et al. 2002) or directing migrating fish away from a high-mortality passage route at the divergence of two rivers (Perry et al. 2014). The deflection bubble screen used only 12 L/s of air per meter of water to reduce passage of Common Carp by 73%, while a cross-stream bubble curtain needed 108 L/s to reduce passage by a similar rate (Zielinski et al. 2014). In the field, reduced demand of air should translate to a significant reduction in the cost of continuously running compressors. Additionally, a deflection configuration might also facilitate trapping and removal.

Finally, our study suggests that the Common Carp could serve as a potential surrogate for studies of how other carp species are influenced by sound. Although the sample size for Bighead Carp we used was small, our findings are consistent with Taylor et al. (2005), who found Bighead Carp passage in a concrete-lined channel was effectively reduced by a bubble curtain paired with speakers. In fact, the reduction in total activity exhibited by Silver and Bighead carp suggests they may be slightly more sensitive to acoustic deterrents than

Common Carp. Using a bubble curtain paired with speakers and strobe light in an Illinois creek, Ruebush et al. (2012) similarly noted a disproportionate upstream passage of Common Carp compared with Asian carp.

In conclusion, our study provides new insight into the theory and application of acoustic deterrents for two Asian carp species and Common Carp. Our findings indicate bubble curtain deflection screens could provide a simple and safe, yet effective means to reduce passage of carp in many locations where other systems are not practical. It also shows that Common Carp could potentially serve as a surrogate for other Asian carp species. We recommend that future applications of bubble curtains be focused on deflecting fish movement rather than outright blockage and that field tests be initiated.

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REFERENCES

Acolas, M. L., J. M. Roussel, J. M. Lebel, and J. L. Bagliniere. 2007. Laboratory experiment on survival, growth and tag retention following PIT injection into the body cavity of juvenile Brown Trout (*Salmo trutta*). Fisheries Research 86:280–284.

ACRCC (Asian Carp Regional Coordinating Committee). 2014. Asian carp control strategy framework. Council on Environmental Quality, Washington, D.C.

Barr Engineering. 2013. Asian carp deterrence alternatives. Prepared for the Minnesota Department of Natural Resources, Executive Summary, St. Paul.

Coutant, C. C., editor. 2001. Behavioral technologies for fish guidance. American Fisheries Society, Bethesda, Maryland.

Dawson, H. A., U. G. Reinhardt, and J. F. Savino. 2006. Use of electric or bubble barrier to limit the movement of Eurasian Ruffe (*Gymnocephalus cernuus*). Journal of Great Lakes Research 32:40–49.

FishPro Consulting Engineers and Scientists. 2004. Feasibility study to limit the invasion of Asian carp into the upper Mississippi River basin. Prepared for the Minnesota Department of Natural Resources and the U.S. Fish and Wildlife Service, Final Report, Springfield, Illinois.

Flammang, M. K., M. J. Weber, and M. D. Thul. 2014. Laboratory evaluation of a bioacoustic bubble strobe light barrier for reducing Walleye escapement. North American Journal of Fisheries Management 34:1047–1054.

Hansen, A., R. Ghosal, J. Caprio, A. W. Claus, and P. W. Sorensen. 2014. Anatomical and physiological studies of Bigheaded Carps demonstrate that the epibranchial organ functions as a pharyngeal taste organ. Journal of Experimental Biology 217:3945–3954.

Huntingford, F. A., G. Andrew, S. Mackenzie, D. Morera, S. M. Coyle, and S. Pilarczk Kadri. 2010. Coping strategies in a strongly schooling fish, the Common Carp *Cyprinus carpio*. Journal of Fish Biology 76:1576–1591.

Irons, K. S., G. G. Sass, M. A. McClelland, and J. D. Stafford. 2007. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA is this evidence for competition and reduced fitness? Journal of Fish Biology 71 (Supplement):258–273.

Johnson, N. S., H. T. Thompson, C. Holbrook, and J. A. Tix. 2014. Blocking and guiding adult sea lamprey with pulsed direct current from vertical electrodes. Fisheries Research 150:38–48.

Kalmijn, A. J. 1988. Hydrodynamic and acoustic field detection. Pages 83–130 *in* J. Atema, R. R. Fay, A. N. Popper, and W. N. Tavolga, editors. Sensory biology of aquatic animals. Springer-Verlag, New York.

Knudsen, F. R., P. S. Enger, and O. Sand. 1992. Awareness reactions and avoidance responses to sound in juvenile Atlantic Salmon, *Salmo salar* L. Journal of Fish Biology 40:523–534.

Kolar, C. S., D. C. Chapman, W. R. Courtenay Jr., C. M. Housel, J. D. Williams, and D. P. Jennings. 2007. Bigheaded Carps: a biological synopsis and environmental risk assessment. American Fisheries Society, Special Publication 33, Bethesda, Maryland.

Ladich, F., and R. R. Fay. 2013. Auditory evoked potential audiometry in fish. Reviews in Fish Biology and Fisheries 23:317–364.

Lovell, J. M., M. M. Findlay, J. R. Nedwell, and M. A. Pegg. 2006. The hearing abilities of the Silver Carp (*Hypopthalmichthys molitrix*) and Bighead Carp (*Aristichthys nobilis*). Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology 143:286–291.

Maes, J., A. W. H. Turnpenny, D. R. Lambert, J. R. Nedwell, A. Parmentier, and F. Ollevier. 2004. Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. Journal of Fish Biology 64:938–946.

Moy, P., I. Polls, J. M. Dettmers, D. Chapman, and M. Hoff. 2011. The Chicago Sanitary and Ship Canal aquatic nuisance species dispersal barrier. Pages 121–137 *in* D. C. Chapman and M. H. Hoff, editors. Invasive Asian carps in North America. American Fisheries Society, Symposium 74, Bethesda, Maryland.

Noatch, M. R., and C. D. Suski. 2012. Non-physical barriers to deter fish movements. Environmental Reviews 20:71–82.

Pegg, M. A., and J. H. Chick. 2004. Aquatic nuisance species: an evaluation of barriers for preventing the spread of Bighead and Silver carp to the Great Lakes. Illinois–Indiana Sea Grant, Final Report A/SE (ANS)-01-01, Urbana, Illinois.

Perry, R. W., J. G. Romine, N. S. Adams, A. R. Blake, J. R. Burau, S. V. Johnston, and T. L. Liedtke. 2014. Using a non-physical behavioral barrier to alter migration routing of juvenile Chinook Salmon in the Sacramento–San Joaquin River delta. River Research and Applications 30:192–203.

Popper, A. N. 1972. Pure-tone auditory thresholds for the carp, *Cyprinis carpio*. Journal of the Acoustical Society of America 52:1714–1717.

Popper, A. N., and T. J. Carlson. 1998. Application of sound and other stimuli to control fish behavior. Transactions of the American Fisheries Society 127:673–707.

Popper, A. N., and R. R. Fay. 2011. Rethinking sound detection by fishes. Hearing Research 273:25–36.

Romine, J. G., N. R. Jensen, M. J. Parsley, R. J. Gaugush, T. J. Severson, T. W. Hatton, R. F. Adams, and M. P. Gaikowski. 2015. Response of Bighead Carp and Silver Carp to repeated water gun operation in an enclosed shallow pond. North American Journal of Fisheries Management 35:440–453.

Ruebush, B., G. Sass, J. Chick, and J. Stafford. 2012. In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp. Aquatic Invasions 7:37–48.

Sager, D. R., C. H. Hocutt, and J. R. Stauffer. 1987. Estuarine fish responses to strobe light, bubble curtains and strobe light/bubble curtain combinations as influenced by water flow rate and flash frequencies. Fisheries Research 5:383–399.

Sampson, S. J., J. H. Chick, and M. A. Pegg. 2009. Diet overlap among two Asian carp and three native fishes in backwater lakes on the Illinois and Mississippi rivers. Biological Invasions 11:483–496.

Sass, G. G., C. Hinz, A. C. Erickson, N. N. McClelland, M. A. McClelland, and J. M. Epifanio. 2014. Invasive Bighead and Silver carp effects on zooplankton communities in the Illinois River, Illinois, USA. Journal of Great Lakes Research 40:911–921.

Silva, A. T., C. Katopodis, J. M. Santos, M. T. Ferreira, and A. N. Pinheiro. 2012. Cyprinid swimming behaviour in response to turbulent flow. Ecological Engineering 44:314–328.

Sisler, S. P., and P. W. Sorensen. 2008. Common Carp and Goldfish discern conspecific identity using chemical cues. Behaviour 145:1409–1425.

Schrank, S. J., C. S. Guy, and J. F. Fairchild. 2003. Competitive interactions between age-0 Bighead Carp and Paddlefish. Transactions of the American Fisheries Society 132:1222–1228.

Sloan, J. L., E. B. Cordo, and A. F. Mensinger. 2013. Acoustical conditioning and retention in the Common Carp (*Cyprinus carpio*). Journal of Great Lakes Research 39:507–512.

Smith, M. E., A. S. Kane, and A. N. Popper. 2004. Noise-induced stress response and hearing loss in Goldfish (*Carassius auratus*). Journal of Experimental Biology 207:427–435.

Stewart, H. A., M. H. Wolter, and D. H. Wahl. 2014. Laboratory investigations on the use of strobe lights and bubble curtains to deter dam escapes of age-0 Muskellunge. North American Journal of Fisheries Management 34:571–575.

Taylor, R. M., M. A. Pegg, and J. H. Chick. 2005. Response of Bighead Carp to a bioacoustic behavioural fish guidance system. Fisheries Management and Ecology 12:283–286.

USFWS (U.S. Fish and Wildlife Service). 2014. The first annual report to Congress: summary of activities and expenditures to manage the threat of Asian carp in the upper Mississippi and Ohio River basins, June 2012 to June 2014. Report to Congress pursuant to the Water Resources Reform and Development Act of 2014, Public Law 113–121, Bloomington, Minnesota.

Varble, K. A., J. J. Hoover, S. G. George, C. E. Murphy, and K. J. Kilgore. 2007. Floodplain wetlands as nurseries for Silver Carp, *Hypopthalmichthys molitrix*: a conceptual model for use in managing local populations. Aquatic Nuisance Species Program, ERDC/TN-ANSRP-07-4, Vicksburg, Mississippi.

Vetter, B. J., A. R. Cupp, K. T. Fredricks, M. P. Gaikowski, and A. F. Mensinger. 2015. Acoustical deterrence of Silver Carp (*Hypophthalmicthys molitrix*). Biological Invasions 17:3383–3392.

Welton, J. S., W. R. C. Beaumont, and R. T. Clarke. 2002. The efficacy of air, sound and acoustic bubble screens in deflecting Atlantic Salmon, *Salmo salar* L., smolts in the River Frome, UK. Fisheries Management and Ecology 9:11–18.

Welton, J. S., W. R. C. Beaumont, M. Ladle, and J. E. G. Masters. 1997. Smolt trapping using acoustic techniques. Phase 1, literature review and initial investigation of acoustic bubble screens. Environmental Agency, R&D Technical Report W66, Bristol, UK.

Wilson, M. R. 2014. Geographic expansion and small stream use by three species of invasive Asian carp in Illinois. Master's thesis. University of Illinois at Urbana–Champaign, Urbana.

Zeddies, D. G., R. R. Fay, M. D. Gray, P. W. Alderks, A. Acob, and J. A. Sisneros. 2012. Local acoustic particle motion guides sound-source localization behavior in the Plainfin Midshipman fish, *Porichthys notatus*. Journal of Experimental Biology 215:152–160.

Zielinski, D. P., and P. W. Sorensen. 2015. Field test of a bubble curtain deterrent system for Common Carp. Fisheries Management and Ecology 22:181–184.

Zielinski, D. P., V. R. Voller, J. C. Svendsen, M. Hondzo, A. F. Mensinger, and P. W. Sorensen. 2014. Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of Common Carp. Ecological Engineering 67:95–103.

RESEARCH ARTICLE

Silver, bighead, and common carp orient to acoustic particle motion when avoiding a complex sound

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Abstract

Behavioral responses of silver carp (*Hypopthalmichthys molitrix*), bighead carp (*H. nobilis*), and common carp (*Cyprinus carpio*) to a complex, broadband sound were tested in the absence of visual cues to determine whether these species are negatively phonotaxic and the roles that sound pressure and particle motion might play mediating this response. In a dark featureless square enclosure, groups of 3 fish were tracked and the distance of each fish from speakers and their swimming trajectories relative to sound pressure and particle acceleration were analyzed before, and then while an outboard motor sound was played. All three species exhibited negative phonotaxis during the first two exposures after which they ceased responding. The median percent time fish spent near the active speaker for the first two trials decreased from 7.0% to 1.3% for silver carp, 7.9% to 1.1% for bighead carp, and 9.5% to 3% for common carp. Notably, when close to the active speaker fish swam away from the source and maintained a nearly perfect 0˚ orientation to the axes of particle acceleration. Fish did not enter sound fields greater than 140 dB (ref. 1 μPa). These results demonstrate that carp avoid complex sounds in darkness and while initial responses may be informed by sound pressure, sustained oriented avoidance behavior is likely mediated by particle motion. This understanding of how invasive carp use particle motion to guide avoidance could be used to design new acoustic deterrents to divert them in dark, turbid river waters.

Introduction

Acoustic energy propagates through water as a traveling pressure wave with accompanying particle motion and is used by fish to mediate numerous life cycle functions including migration, communication, prey detection, and avoidance. To use sound efficiently, fish need to be able to both distinguish signals above background noise and then use this information to orient, or move in a directed fashion. While sound pressure, a scalar quantity, cannot provide fish with any immediate directional information on its own, particle motion, a vector quantity, is

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inherently directional and could. However, although the capacity for directional hearing in fish is relatively well described [1–4], only a handful of experimental studies have tested how it is mediated. These studies have shown that both sound pressure and particle motion can play very different, and independent roles in the oriented movement of fish seeking a sound source (positive phonotaxis) [5–9]. In contrast, although sound induced repulsion (negative phonotaxis) has also been described in a few species of fish, the sensory cues responsible for these responses have not yet been explicitly described so are unknown [10–14]. How fish might orient toward and away from sound sources has both basic implications for understanding how fish might use sound to meet their ecological needs as well as strong implications for how sound might be used to either attract or repel fishes of concern in the natural world. The present study characterized the orientation mechanisms used by three species of invasive carp as they avoided a sound source and the two sensory fields it created in the absence of visual cues.

All teleost fishes are similarly equipped to detect particle motion, but their abilities to detect sound pressure vary greatly. Particle motion is detected via a fish's inner ear otolithic end organs, which function as accelerometers when their dense otoliths move in response to the acoustic field over a sensory epithelia with polarized hair cells [15]. Particle motion detection by its very nature has a distinct directional component. Conversely, sound pressure, which lacks directional information, is only detected with notable sensitivity by fish which possess an acoustic coupling (i.e. Weberian apparatus) between a gas-filled pocket (generally the swim bladder) and their inner ear [16–18]. Fish that have evolved notable sensitivity to sound pressure have a wider hearing bandwidth and greater sensitivity than species without specializations [4]. While both particle motion and sound pressure are also detected by the mechanosensory lateral line in all fishes, it only detects low frequencies (< 300 Hz) and only in the acoustic near-field [19–20], so sound sensitivity in fish is in most instances attributable to the inner ear.

Both sound pressure and particle motion based orientation mechanisms have now been described in two fish species by carefully describing the approach pathways they take to locate sound sources. In the first example, the female plainfin midshipman, *Porichthys notatus*, was found to locate the sound of calling mates in a featureless dim environment by swimming in a direction that had a near constant angle to the axis of acoustic particle motion [7–9]. In contrast, blinded mottled sculpin, *Cottus bairdi*, was found to use sound pressure to locate a dipole sound source (50 Hz) by swimming in a distinct zig-zag swimming pattern [5,6]. By zig-zagging, sculpin were seemingly able to assess the relative intensity of sound pressure at different locations, and thus orient. These two orientation strategies which employ particle motion and sound pressure are markedly different from each other. Orientation mechanisms have not yet been explicitly described for fish avoiding sound which is complicated because acoustic signal intensity drops with distance, making comparisons of relative intensity more difficult.

Two species of bigheaded carp from Asia, the silver carp (*Hypopthalmichthys molotrix*) and the bighead carp (*H. nobilis*) were introduced to the United States in the 1970s, and have become highly abundant and invasive in the Mississippi River. Because these fish adversely impact aquatic food webs [21–24] and one jumps; there is strong interest in developing technologies to block their expansion up the Mississippi River [25]. Similarly, the common carp (*Cyprinus carpio*), a related cyprinid from Eurasia [26], is also invasive and has been responsible for degrading millions of acres of shallow wetland ecosystems across the globe so there is interest in stopping its movement between waterways [27]. All carps are Ostariophysians and have well developed hearing abilities that include a heightened sensitivity to sound pressure, which is superior to that of many native North American fishes [28–30]. Accordingly, it has been proposed that acoustic deterrents might be used to block the access of invasive carps to critical habitat [10,11, 31–38]. Recently, Vetter et al. [10,11] demonstrated that large groups of silver carp and bighead carp exhibited negative phonotaxis to a complex outboard motor sound when tested in a well-lit arena with exposed speakers when sound was repeatedly played when fish approached a specific location. While the distance of the apparent centroid of the fish school was measured relative to the sound source, the positions and orientations of individuals were not tracked to determine specific angles of orientation to any sound cues, so whether the observed responses were oriented to the sound field, or influenced by the physical presence of the speaker (which was visible to fish) were unclear. The particle motion component of sound that was played and its possible role relative to carp bearing was also not assessed so its role was similarly unclear. Thus, while intriguing, the implications of this work to understanding orientation and deterrence to sound and its possible applications to riverine acoustic barriers in dark or turbid / featureless waters are unclear. Indeed, no study that we know of has determined the orientation mechanisms used by any fish to avoid sounds by precisely mapping movement relative to known sound pressure and particle motion fields in the absence of visual cues.

The present study investigated the nature of behavioral responses of silver, bighead, and common carp to a stationary, monopole sound source to characterize whether and how these species avoid complex sound in the absence of visual cues. Specific goals were to: (1) determine whether silver, bighead, and common carp are all negatively phonotaxic (i.e. move away from the sound source) to complex, broadband sounds in the absence of visual cues, and (2) test the relative roles of sound pressure and acoustic particle motion in this response. A complex, broadband outboard motor sound was used because it had already been tested by Vetter et al. [10,11] and had also previously been shown to induce physiological stress responses in the common carp [39].

Materials and methods

Experimental animals

Juvenile silver carp [mass: 120 ± 41 g (mean ± SD); total length: 237 ± 35 mm] and bighead carp [mass: 32 ± 16 g; total length: 139 ± 21 mm] were obtained from the Columbia Environmental Research Center (U.S. Geological Survey, Columbia, MO, USA) and held in circular 100-L tanks until needed. Bigheaded carp were fed a planktonic diet consisting primarily of Spirulina and Chlorella algae (see [40]) once a day between 10:00 h and 14:00 h. Common carp [mass: 416 ± 113 g; total length: 298 ± 25 mm] were caught in Casey Lake, MN, USA (45˚ 01’22” N, 93˚00’49” W) by pulsed DC electrofishing in July 2012 and transported to the laboratory, where they were maintained in tanks (1.5 m diameter x 50 cm deep). Common carp were fed pellets (Silver Cup, Utah) once a day between 10:00 h and 14:00 h. Fish were held at a 16h:8h (L:D) photoperiod and all holding and experimental tanks were supplied continuously with flow-through 20˚C well water. All experimental procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1201A08922), and all necessary federal and state permits for shipping and holding prohibited species were also obtained.

Experimental setup

Experiments were performed in a cylindrical fiberglass tank (3 m diameter, 2 m in depth) into which an internal square opaque plastic enclosure (1.8 m on a side, 50 cm high, 150 μm thick) had been placed to render the testing arena featureless (Fig 1). The center of the arena had a drain pipe which was also shielded with a black plastic box (50-cm high on each side). This tank was supplied with well water to a depth of 30 cm and aerated by airstones positioned outside of the enclosure in each corner. A black plastic tarp covered the entire tank and three

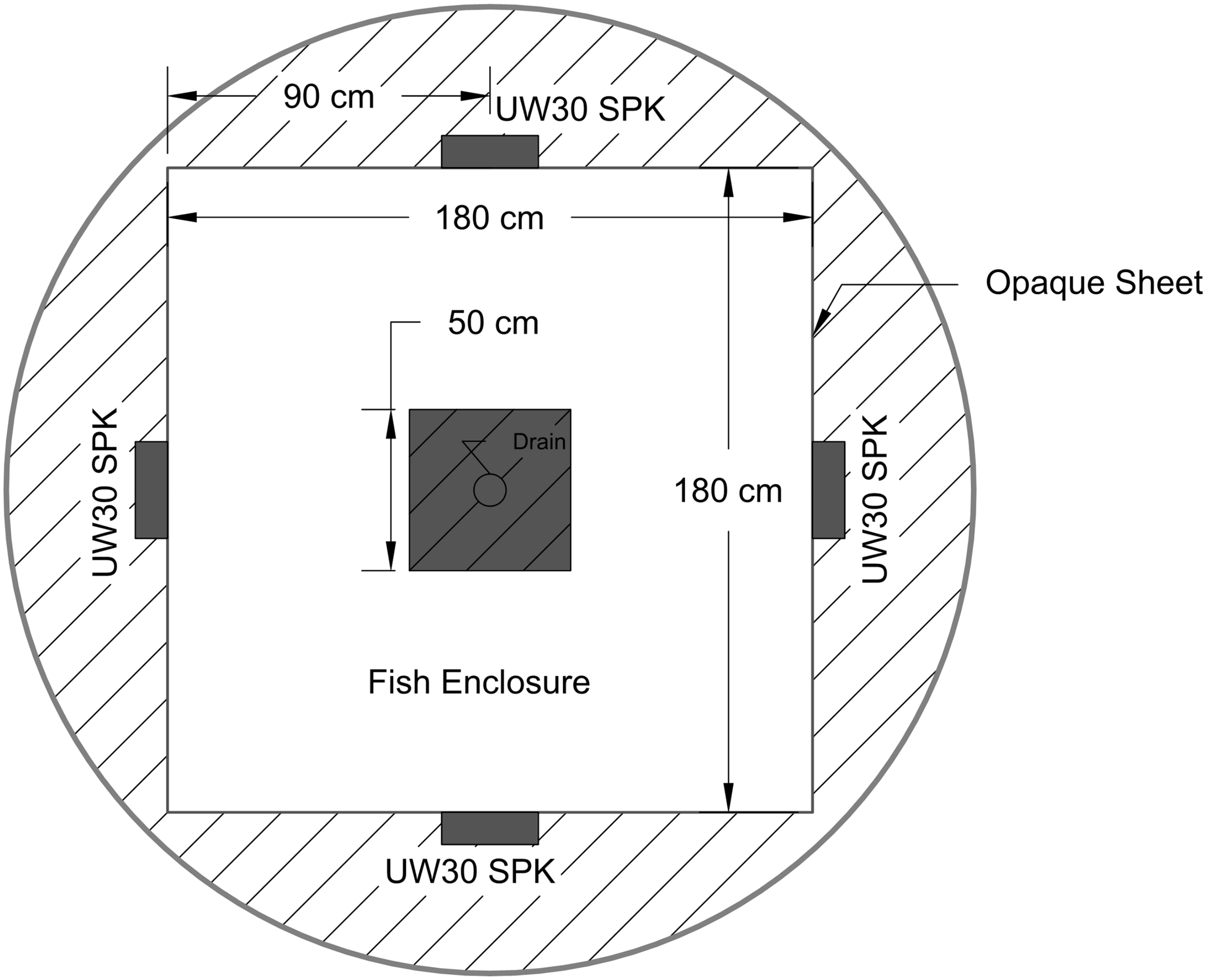

Fig 1. Schematic of the experimental tank showing the locations of the speakers, plastic enclosed testing arena, and drain cover box. The outside diameter of the tank was 3 m and the water depth was 30 cm. The tank was darkened by a black plastic tarp which covered it and illuminated by infrared lights.

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infrared floodlights (840 nm) illuminated the inside of a darkened arena. Light levels were extremely low (0.5 μW/cm^2) and the tank devoid of obvious visual cues, so it is highly unlikely that vision would have been useful to fish even though the common carp's visual sensitivity extends into the infrared (870 nm) [41] (the visual sensitivity of bighead and silver carp has not been reported). Four UW30 speakers (output level 153 dB (ref. 1 μPa) at 1 m, frequency response 0.1 to 10 kHz, Electrovoice, MN, USA) were positioned outside the plastic arena (so they were not visible) at the center of each side using cables that acoustically separated them from the tank and set the center of the speaker 15-cm above the tank floor. A closed circuit video camera (Interlogix, NC, USA) was mounted 3 m above the tank bottom, and recorded at 30 frames per second through each experiment. Video files were later downloaded from a DVR and a custom Matlab (Mathworks, MA, USA) script was used for frame-by-frame analysis.

Acoustic stimuli

We tested a complex, broadband sound that had been recorded from a 40 hp outboard motor. Sound was played for 120-s via speakers when fish were within 30 cm (see experimental design section for details) and produced a peak sound pressure level (SPL) of approximately 150 dB (ref. 1 μPa) directly in front of each speaker with most of its energy within two peaks around 150 Hz and 2000 Hz (Fig 2A). Similar to Vetter et al. [11], the sound field measured in the tank differed slightly from the original signal at low frequencies due to the speaker frequency response (S1 Fig) The frequency range of the playback signal overlapped the hearing range for common carp [28] which is also very similar to the hearing ranges of silver and bighead carp [29,30], 50–3000 Hz (Fig 2A). The background sound pressure level was below 80 dB (ref. 1 μPa) throughout the enclosure when inflow and airstones were turned off. Sound pressure contours decreased in a radial fashion away from the speaker (Fig 3) and differed by less than 5% between all four speakers (see S2 and S3 Figs for sound pressure contour of entire enclosure and radial attenuation of sound pressure level). Particle acceleration was approximately 20 dB (ref. 1 cms^{-2}) in front of the speaker with most of the energy within three peaks around 150, 1000, and 2000 Hz (Fig 2B). Particle acceleration vectors in the *xy*-plane were orthogonal to sound pressure contours, pointing towards (or away from) the projector (Fig 3). Particle acceleration was similar in all three directions throughout the tank (S4 Fig).

Both sound pressure levels and particle acceleration were mapped on a Cartesian grid throughout the tank at 5-cm intervals within 30-cm of each of the four speakers and 15 cm above the tank bottom. Sound measurements were made using a PVC probe similar to that used by Zeddies et al. [8], which contained a C55 hydrophone (usable frequency range of 0.008–100 kHz and a sensitivity of approximately -163.5 dB ref 1V/μPa, Cetacean Research, WA, USA) and a PCB model W356A12 triaxial accelerometer (usable frequency of 0.5–5000 Hz and sensitivity of approximately 100 mV/ (m/s^2), PCB Piezoelectronics, NY, USA). The

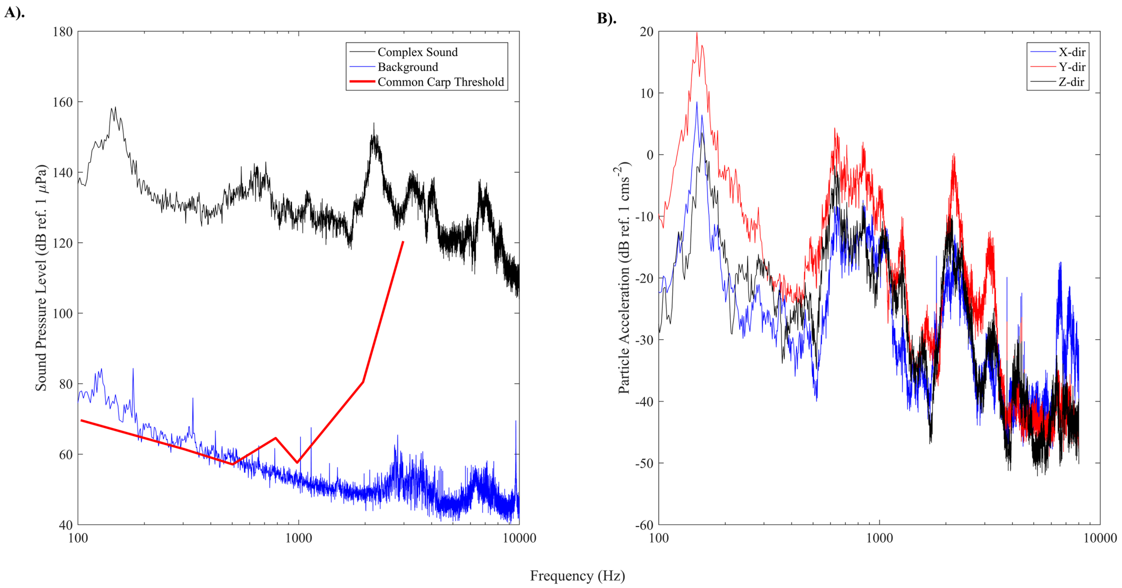

Fig 2. A) Sound pressure level power spectrum of the background noise, playback signal 5 cm from the speaker, and hearing threshold of common carp (from Popper, 1972). B) Particle acceleration measurement in decibels (ref. 1 cms^{-2}) in each direction at a point 5 cm in front of the speaker. Sound pressure level and particle acceleration measurements are provided at 1 Hz bandwidth. Note, the 1 cms^{-2} limit suggested by Knudsen et al. [42] is at 0 dB (ref. 1 cms^{-2}).

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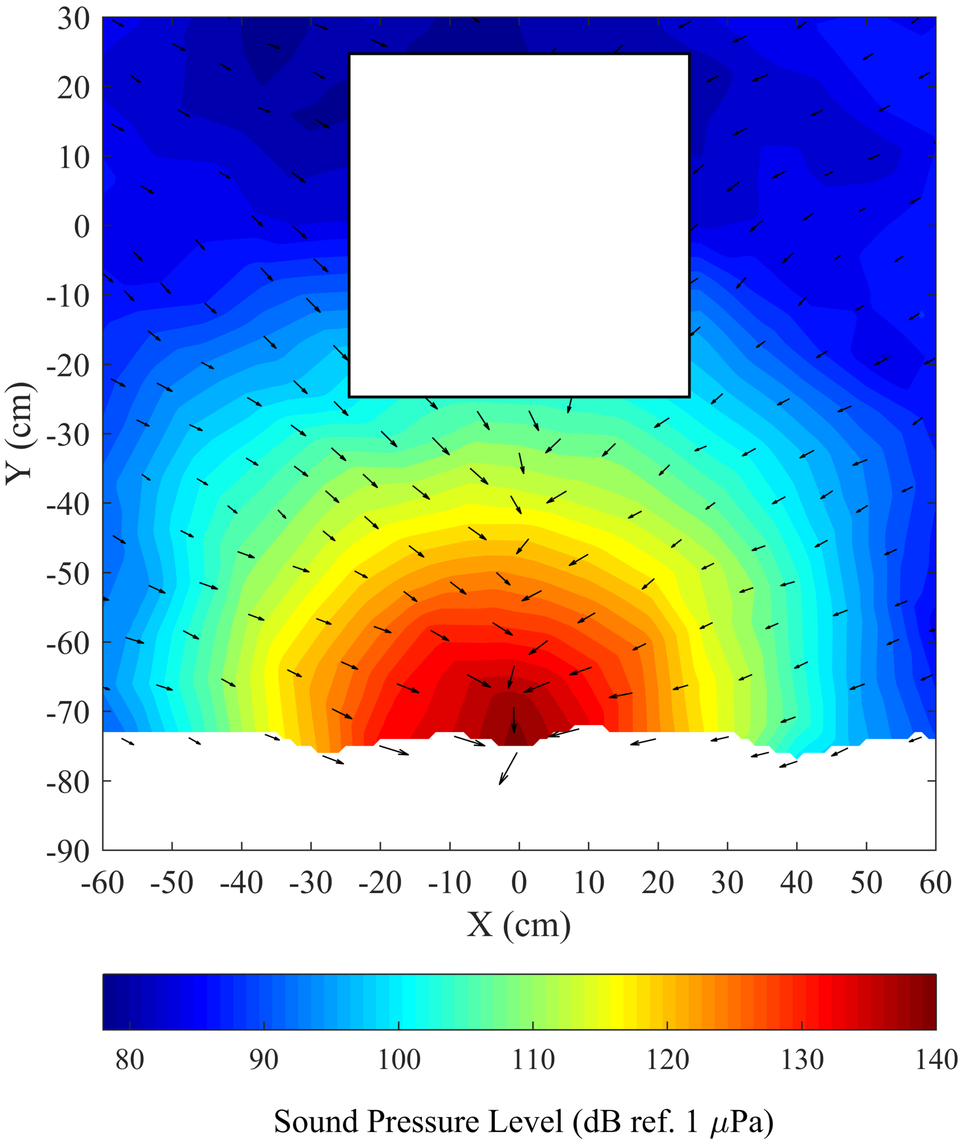

Fig 3. Plan view of sound pressure level in dB (ref 1 μPa) at 2000 Hz in the enclosure at a depth of 9 cm from the tank bottom with particle acceleration vectors in *xy*-plane. Particle acceleration magnitude is calculated using only the acceleration in the *x*- and *y*-directions. The speaker was hidden behind a plastic enclosure and located at 0 cm on the X-axis, with the center of the projector face 15 cm from the tank bottom. Contours do not extend to 90 cm because acoustic instrumentation could not be placed closer to the plastic enclosure.

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sound pressure signal was sampled at 44.1 kHz and fed through a TASCAM US-122mkII (TASCAM, CA, USA) audio interface, digitized, and stored on a windows-based computer. The accelerometer was neutrally buoyant because it had been embedded in an extruded polystyrene foam enclosure. The acoustic particle acceleration signal was conditioned using a PCB 482C05 conditioner and fed through a USB-1208FS-Plus data acquisition board (Measurement Computing, MA, USA) sampling each channel at 16 kHz. At each location, a 10 s sample was split into 10 signal ensembles and averaged. Data acquisition hardware was controlled by a custom graphical user interface operating in Matlab, which was also used to analyze and transform the pressure and particle acceleration waveforms into the frequency domain.

Experimental design

Tests were conducted between 10:00 and 16:00 h between December 2013 and August 2014. Fish were tested as groups of three individuals of the same species to facilitate natural shoaling behavior and reduce stress [43,44]. Prior to testing, fish were allowed to acclimate, shoal, and move freely. Acclimation times differed by species and had been determined beforehand by extensive pilot tests as the periods of time required by fish to start to explore tanks and feed when offered food (130 min for common carp, 20 min for silver carp, and 24 h for bighead carp). Water inflow and airstones were turned off 10 min prior to the start of each trial. After the 150 s pre-test period (control), the test sound was played once two individual carp swam within 30-cm of any one of the four speakers, at which time that speaker was turned on for 150-s (treatment). The 30-cm distance was used as a threshold because sound mapping showed it to coincide with both the region of maximum sound pressure and the 1 cms^{-2} particle acceleration limit for avoidance behaviors previously prescribed by Knudsen et al. [42] and Karlsen et al. [45]. This procedure was repeated for four trials (each with a control and treatment period) until all four speakers had been used once (time between trials varied, and fish could not learn order of testing). After testing, fish were removed and placed into a control tank. Each species was tested 7 times and no fish were reused.

Analysis of fish distribution and orientation

Data were evaluated in two steps. Step one evaluated fish distribution (i.e., avoidance) while step two determined the tracks that individual carp followed (i.e., orientation) and then evaluated how fish oriented to known sound fields to discern the orientation mechanisms they were using.

Fish distribution and avoidance. For the first analysis, the percent time each fish spent within 30-cm of the active speaker (or the soon-to-be active speaker for control periods) was calculated after viewing videos. This was accomplished by recording the x and y coordinates of each fish's head within each group of three at 5 s intervals (i.e. once every 150 frames). Initial plots of fish movement showed that fish rapidly moved in the first few seconds of sound exposure before assuming a more constant distribution (S5 Fig), so we chose to exclude the first 30 s of their behavior from this particular analysis to assess their long-term responses and avoidance. For each group of fish (and trial), the percent time fish spent within 30-cm of the active speaker (after the first 30 s) was calculated by dividing the total number of times any fish was within 30-cm of the active speaker by the total number of data points. These values were examined for normalcy (Shapiro-Wilk tests) and appropriate paired comparisons performed. Because the data were not normally distributed nonparametric Mann-Whitney U-tests [46] were used to compare differences in the percent time that groups of fish of each species spent within 30-cm of an active speaker between matched control and treatment periods (i.e. Control #1 vs. SPK#1, Control #2 vs. SPK#2, etc.). Significance was determined at $P<0.05$. All assumptions of these tests were met.

Fish orientation. The second set of analyses examined the relationship between the orientation of individual fish to different components (sound pressure and particle motion) of the sound field and its source. Movement data from the full 150 s test period was used in this analysis (i.e., the first 30 s was not excluded). To accomplish this we calculated both the difference angle between the fish's bearing relative to the sound source as well as the difference angle to the sensory field (particle acceleration vector) following Zeddies and others [5–9] (Fig 4). If sound pressure alone mediated phonotaxic responses, we hypothesized that fish would swim either directly away from the source (180°) or exhibit zig-zag movements to assess changes in relative sound pressure (as described for the mottled sculpin). Alternatively, if particle motion

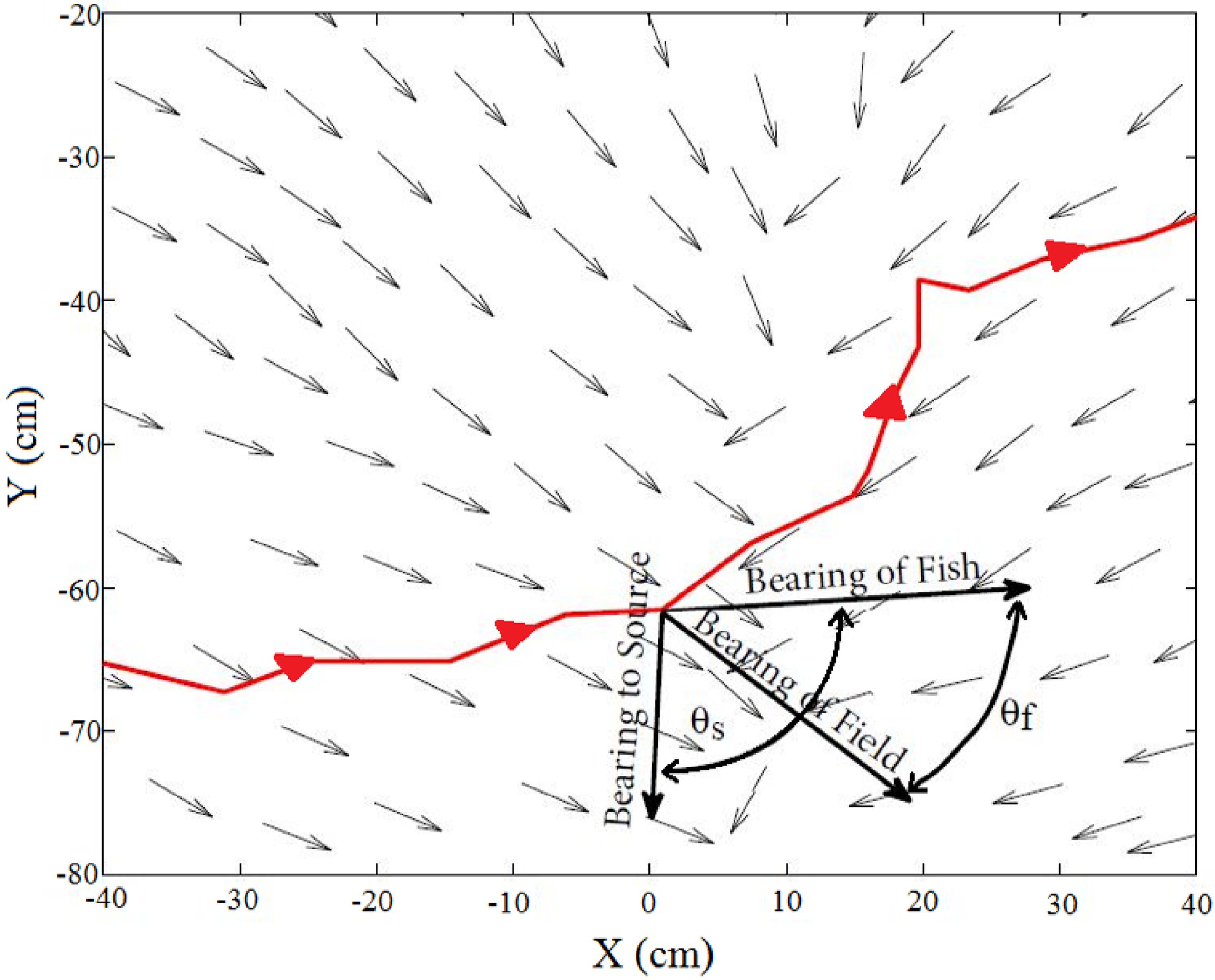

Fig 4. Difference angle of the fish's bearing relative to the sound source (located at X = 0 cm), θ_S, and the local particle acceleration vectors, θ_F, at a given location along an individual swimming trajectory. Small arrows indicate local particle acceleration vectors (normalized for visual comparison), and the solid line indicates a sample swimming trajectory. Difference angles were calculated with reference to the origin (i.e. both difference angles in the example would have a negative value).

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detection alone was the basis of orientation, the difference angle of the fish to the particle acceleration vectors was expected to be both nearly constant [47] and in line with the particle motion vector; in other words, it would be a relatively constant 0˚ [7–9].

Swimming trajectories were determined for each fish that swam within 30-cm of an active speaker at a 3 Hz sampling frequency. The position of each fish was evaluated 5 s before and after coming within 30-cm of the speaker, so fish were monitored to distances that might occasionally exceed 30-cm (some up to 125 cm). The entire treatment period was evaluated for each fish found in this space. The x and y coordinates of each fish's head were used to determine both their distance from the source and orientation relative to measured sound fields. To test whether they orientated differently as they approached and then left the sound field, difference angles were analyzed separately as fish swam towards and away from the speaker. Both the difference angle relative to the speaker,θ_S, and difference angle relative to the local particle acceleration vector,θ_F, were calculated from the fishes trajectory in the xy-plane (Fig 4).

Contributions of particle acceleration in the z-direction were ignored because particle acceleration magnitudes were similar throughout the enclosure in all three-directions (S4 Fig) and fish movement was laterally restricted. When fish were not located at a specific measurement point, the vector was interpolated linearly. Finally, difference angles were binned at 10-cm increments from the source and circular statistics used to calculate the mean angle, standard deviation, and vector strength [48]. Vector strength was used as a measure of the directional tendency of fish to move in a specific direction relative to either the source or particle acceleration axes (i.e. a value of 0 indicates difference angles were uniformly distributed, while values close to 1 indicates a concentration in one direction). The Rayleigh test was used on each group of binned difference angles to test whether they differed from random ($P<0.05$) [48]. Bearing to the speaker was used to compare swimming trajectories of fish when the sound was off (control) and then while it was on (treatment). This type of comparison could not be made using particle motion as no sound was played during controls. Sound pressure level at the fish's location was also calculated along each individual swimming track and binned with the mean value and standard deviation calculated to determine if sound pressure might act as a threshold for behavior change.

Results

Fish distribution and avoidance

The median percent time fish spent within 30-cm of speakers during all 4 control periods (which a separate analysis showed not to differ between trials) was 9.5% [4.3, 11.8] (median [1st and 3rd quartiles]) for common carp, 7.0% [4.3, 9.7] for silver carp, and 7.9% [3.2, 11.8] for bighead carp. During the first playback the median percent time fish spent within 30-cm of the active speaker decreased to 3.0% [1.3, 5.3] for common carp, 1.3% [0.0, 2.3] for silver carp, and 1.1% [0.0, 1.3] for bighead carp, a decrease of at least two-thirds of control values (Fig 5). A

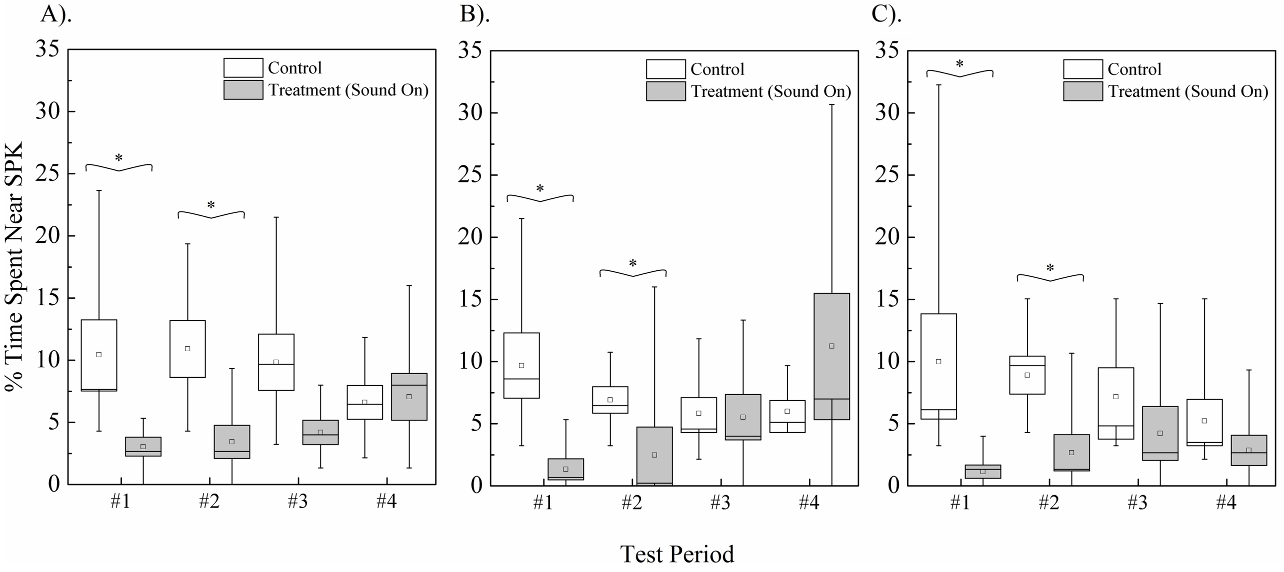

Fig 5. Percent time (A) common carp, (B) silver carp, and (C) bighead carp spent within 30-cm of a speaker before and during activation. Box plots illustrate data quartiles, mean (line), median (squares), and whiskers represent minimum and maximum values. Data from each species was analyzed separately with Mann-Whitney pair-wise comparisons, with (*) denoting mean times with significant difference P<0.05.

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similar decrease was observed for all three species during the second playback. No measurable change was observed for any species during either the third or fourth trials ($P>0.05$).

Orientation

A total of 45 common carp, 29 silver carp, and 26 bighead carp swimming trajectories were tracked and analyzed throughout all four trials. Plots during control periods showed that carps tended to follow the boundary walls at a distance of about 10–40 cm (Fig 6). In contrast, when the sound was turned on, individual fish showed a strong tendency to slowly turn while gradually increasing their swimming speed, thus resulting in their avoiding the location of the active speaker as they swam along curved tracks about 20–30 cm from the active speaker (Fig 6). Notably, the fish consistently maintained a nearly 0˚ orientation to local particle acceleration vectors while pursuing this behavior (Fig 7). Analyses showed that their exposure to sound pressure along the swimming trajectories consistently increased during approach and declined during avoidance at similar rates (Fig 8). No changes in swim paths, or apparent zig-zagging behavior were noted as fish approached or swam away from the sound source and a few fish seemed to employ c-starts. While common carp and bighead carp did not enter areas of the arena where sound pressure exceeded 140 dB (ref. 1 μPa), silver carp stayed further away and did not enter areas where sound pressure exceeded 130 dB (ref. 1 μPa). The difference angle to the sound source for all three carps showed similar trends with no apparent difference in mean angle when the sound was off (control) or on (treatment) (Fig 9). In both cases, difference angles started slightly negative and then increased as the fish approached the sound source, reaching 45˚ when within 30-cm, and followed a similar relationship as fish swam past the speaker. Further, error bars also did not increase dramatically near the source suggesting that carp swam in a very consistent, oriented fashion.

When the sound was on, all fish exhibited a high degree of directional tendency with respect to particle acceleration vectors (vector strength > 0.7 at distances between 30–120 cm for common carp, 30–95 cm for silver carp, and 30–108 cm for bighead carp). The difference angle to particle acceleration vectors varied when fish started to swim away from the speaker (i.e. vector strengths at bin locations within 30-cm of the speaker were below 0.7 for all species). Visual inspection of the plots suggested this variation was seemingly caused by fish reversing direction and moving out of alignment with the particle acceleration vectors for brief periods of time. Difference angles to the particle acceleration vectors differed from random for all three species up to a distance 80 cm from active speakers (Raleigh, $P<0.05$).

Discussion

This study found that silver, bighead, and common carp exhibited negative phonotaxis when exposed to the sound of a complex, broadband sound in a dark, featureless environment but that this response habituated. Avoidance behaviors were strongly and consistently characterized by individual fish swimming along a curvilinear trajectory when sound pressure reached about 130–140 dB (ref. 1 μPa) (at a distance of 30 cm) from a hidden speaker and then swimming parallel to the axes of local particle acceleration before leaving the sound field. All carp followed extremely consistent trajectories with a nearly perfect 0˚ orientation to the axes of local particle acceleration. All three carp species showed very similar behaviors. Given the comparable hearing abilities of these species, it is not surprising that their avoidance responses and orientation strategies were similar. These results suggest that while pressure sensitive fishes such as carp and other ostariophysians may become aware of aversive sound by detecting changes in sound pressure, they likely then use particle motion to orient avoidance

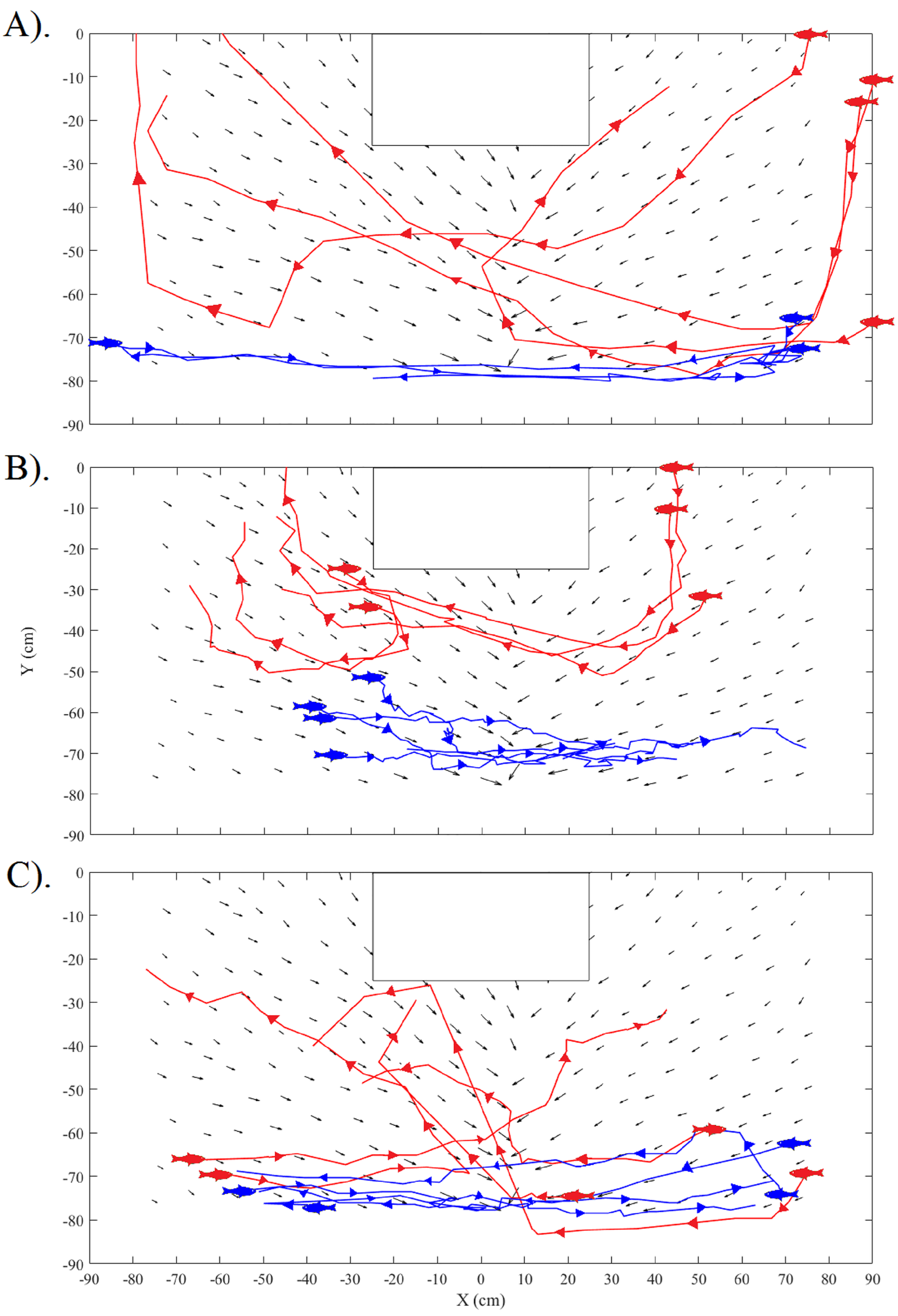

Fig 6. Representative responses of (A) common carp, (B) silver carp, and (C) bighead carp during control (blue lines) and treatment (red lines). Particle acceleration vectors are shown for reference. A fish symbol denotes the start and arrows indicate direction of movement. Note trajectories follow a curvilinear path parallel to local particle acceleration vectors during treatment periods, while trajectories follow paths parallel to the enclosure wall during control periods.

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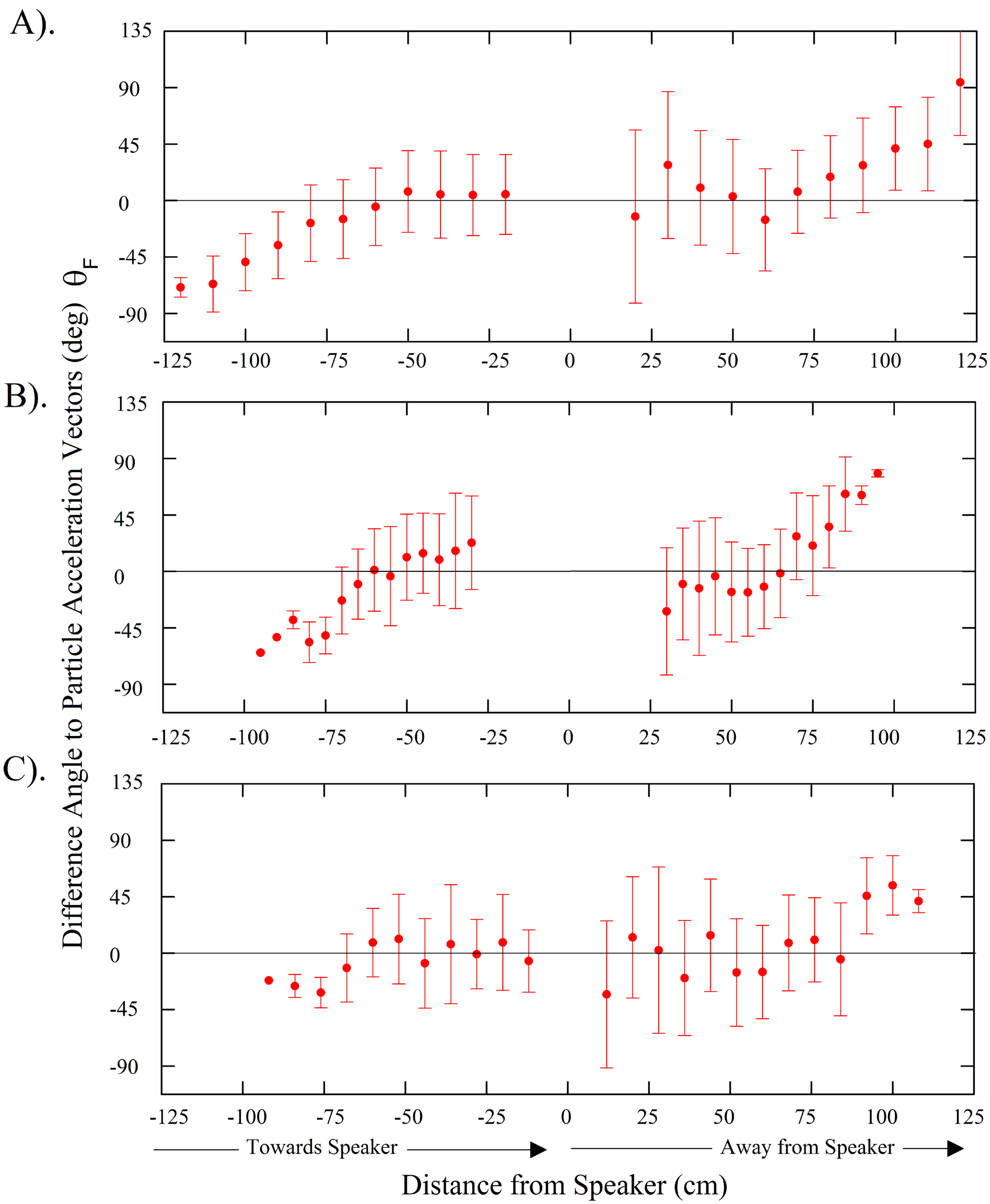

Fig 7. Difference angles of fish bearing relative to the local particle acceleration vectors for (A) common carp, (B) silver carp, and (C) bighead carp. Difference angles were calculated along swimming trajectories of fish that swam within 30-cm of an active speaker during playback. Trajectories were analyzed from all four trials. Negative distances indicate movement towards the speaker, while positive indicate movement away. Bars are the standard deviation.

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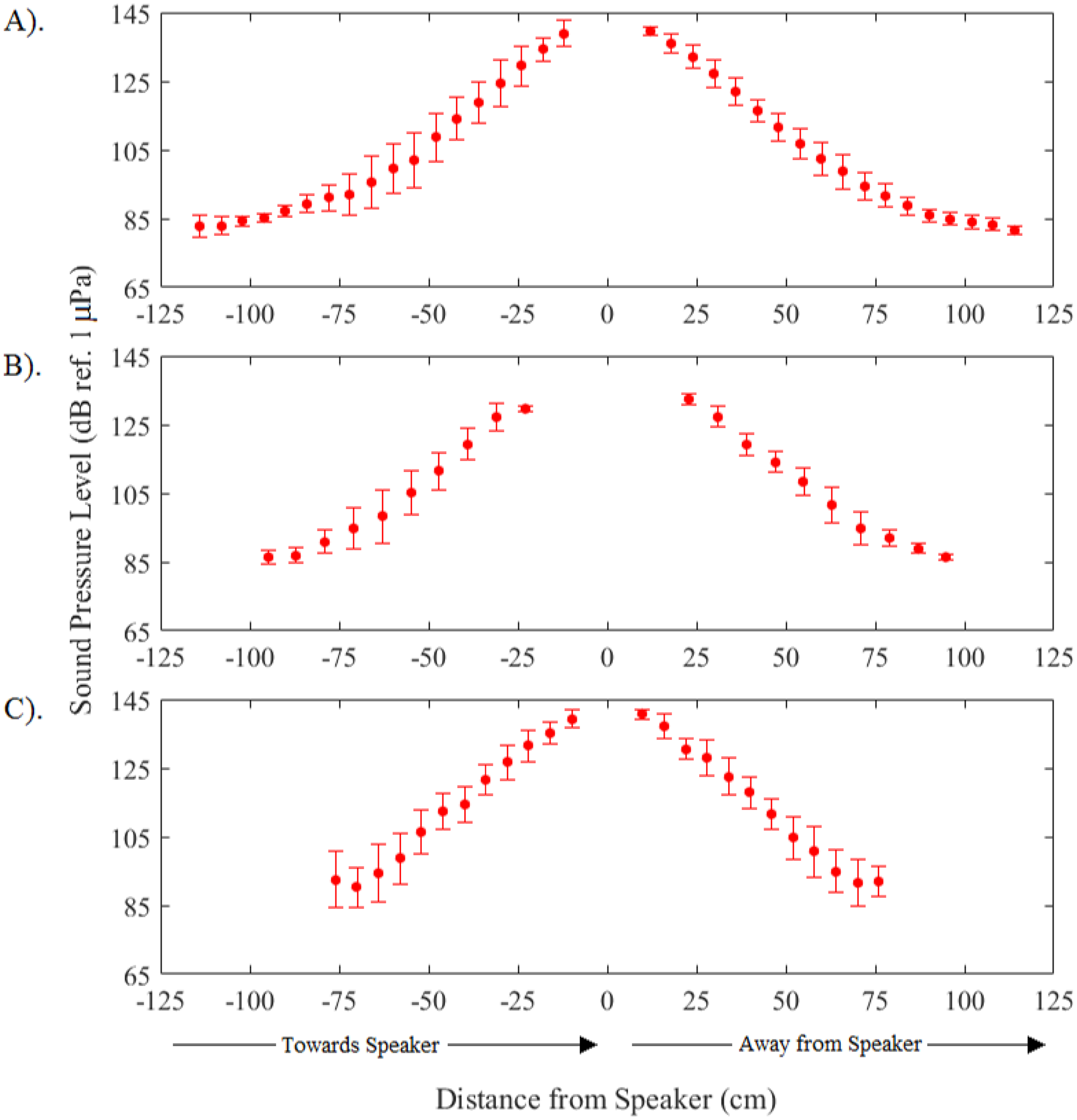

Fig 8. Mean sound pressure level along swimming trajectory of (A) common carp, (B) silver carp, and (C) bighead carp. Trajectories were analyzed from all four trials. Negative distances indicate movement towards the speaker, while positive indicate movement away. Bars are the standard deviation.

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responses in the absence of visual landmarks. Presumably this would be the case in turbid river waters.

This study appears to be the first to describe the acoustic basis of negative phonotaxis in any fish and shows a clear role for particle motion, at least when visual landmarks are not available. Although carp are sensitive to sound pressure, and do appear to sense it as indicated by

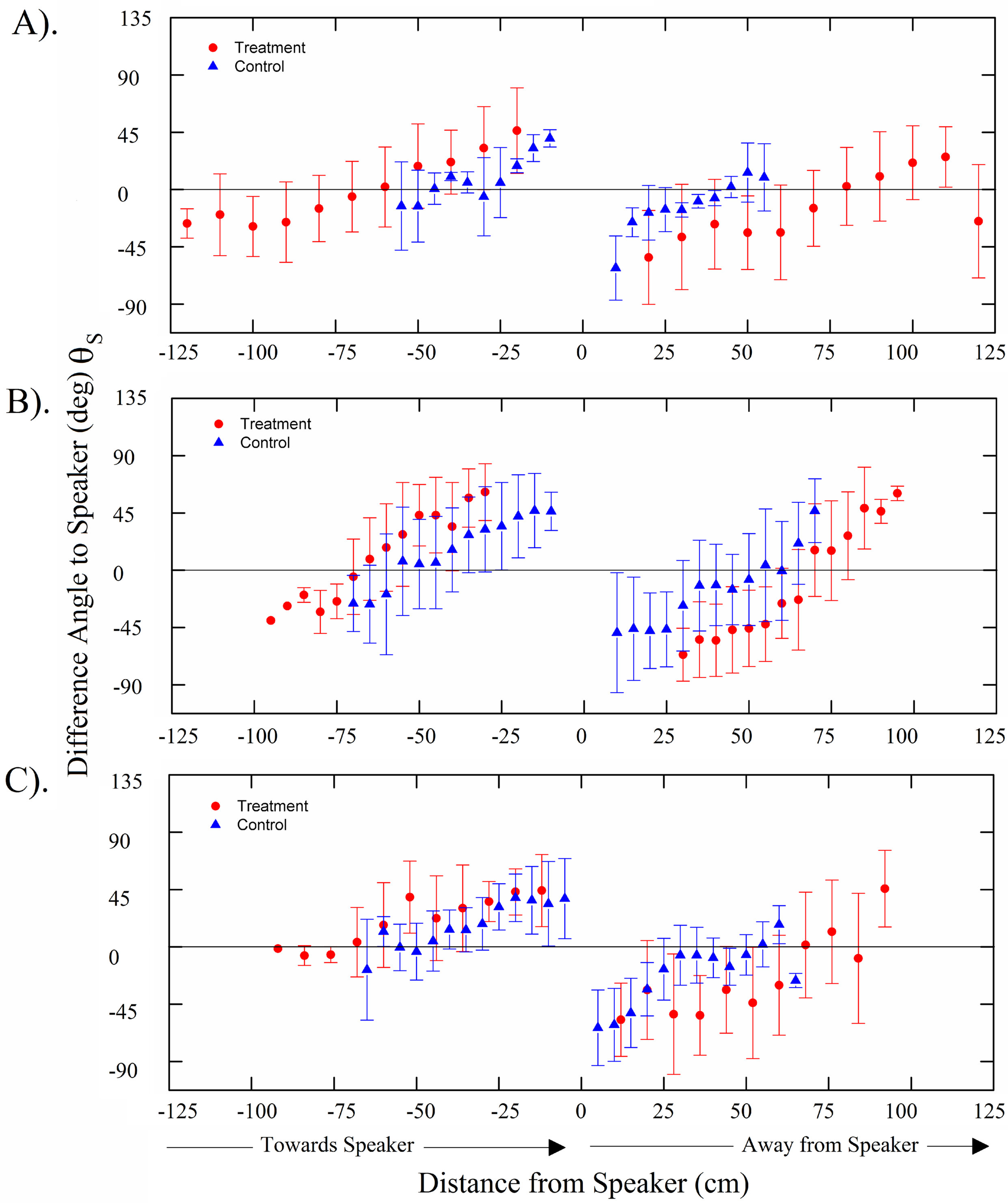

Fig 9. Difference angles of fish bearing relative to the speaker for (A) common carp, (B) silver carp, and (C) bighead carp. Difference angles were calculated along swimming trajectories of fish that swam within 30-cm of an active speaker during playback (treatment ●). Difference angles relative to the speaker are provided for 8 trajectories during control periods (control ▲). Trajectories were analyzed from all playbacks treatments. Negative distances indicate movement towards the speaker, while positive indicate movement away. Bars are the standard deviation.

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their reluctance to enter fields greater than 140 dB (ref. 1 μPa), all three carp species appeared to primarily use particle motion to orient away from the sound source as indicated by their near perfect orientation to the axes of particle acceleration. All three species of carp also started to orient to the particle acceleration axes when 50–75 cm from the sound source, a distance where sound pressure levels were marginally different from background. This set of observations strongly suggest that a particle acceleration of -25 dB (ref. 1 cms^{-2}) is sufficient for these fish to orient and determine direction. The highly consistent nature of this behavior is consistent with both the directional nature of particle motion and how it is used by plainfin midshipman [7,8]. Notably, it differs notably from the zig-zagging behavior exhibited by the mottled scuplin which employed sound pressure via their mechanosensory lateral line to locate sound sources [5,6]. Orientating to local particle motion provides an efficient (i.e. less time and energy expense) pathway away from the source in the absence of other cues. While this study does not isolate the role of particle motion detection at the inner ear from the lateral line, ablation of the plainfin midshipman fish lateral line did not reduce phonotaxic behaviors [9], suggesting the role of input from the lateral line may be minimal in acoustically mediated orientation. The curved nature of the swimming paths observed in this study are consistent with avoidance behaviors of bigheaded carps and common carp previously seen to low frequency (< 5000 Hz) sound sources produced by air curtains in darkness [31–33]. The plainfin midshipman also swims in a directed linear fashion when approaching the sound produced by calling mates [7–9]. Similarly, the allis shad (*Alosa alosa*) is also known to swim at an angle of 180 ±30° to avoid sounds simulating those made by toothed whales (40 kHz clicks) [12–14] although its swimming paths have not been described as we have done.

While clearly showing that carp orient to particle motion, our results are consistent with the possibility that sound pressure may also play a role in initial phases of acoustically mediated behaviors of these species. Individuals started to avoid the active speaker when sound pressure levels reached 130–140 dB (ref. 1 μPa). When carp were near an active speaker, fish selected trajectories with sound pressure levels that increased and decreased gradually with minimal fluctuations. This differed markedly from the zig-zag trajectory used by mottled sculpin to sample the sound field and use for sound localization [5,6]. The role of pressure detection in source localization cannot be ascertained from these results, as this relationship is yet to be thoroughly defined for any species [9]. Taken together, our results suggest that while sound pressure may initiate the avoidance responses, particle motion ultimately guides carp movement in the absence of other cues.

Importantly, our study found that avoidance behavior in carp habituated with repeated testing, at least in darkness. This is not surprising, because habitation is common to all sensory cues used by organisms [49], and especially for continuous signals [50,51]. Transient hearing damage may have been one potential cause, but the exposure time of 150 s and sound pressure level 130–150 dB (ref 1 μPa) used in our study was far less than the 10 min period and 170 dB (ref 1 μPa) reported to cause a temporary threshold shift in goldfish (*Carassius auratus*), arguing against this. Our findings were undoubtedly influenced by the small size of our tank which provided no acoustic refuges and an anomalous sound field [52], especially because air surrounding the fiberglass tank creates a pressure release (i.e., sound pressure is zero but particle motion is not zero) along all boundaries which causes significant reflections of sound. This is different from natural water bodies that would only have a pressure release boundary at the water surface. Small tanks and shallow water also impact propagation of low frequency sounds due to boundaries interacting with sound wavelengths larger than the minimum dimensions of the tank or water depth [53]. To minimize issues related to small tank acoustics [54] we kept fish in the center of the tank and away from the complex sound field near the tank walls, sound field measurements were made at sufficiently fine spacing to capture any rapid changes in space, and both the sound pressure and particle acceleration fields were characterized. Although our findings that carps orient to particle motion cannot be directly applied to how fish might respond to natural sound fields in large open arenas, our basic finding that they respond to these fields is relevant.

While our findings are consistent with those of Vetter et al. [10,11] who found that groups of silver and bighead carp exhibited negative phonotaxis to a complex sound in a well-lit environment, they differ because we observed habituation and did not find that carp swam directly away from the sound source as they did. These apparent discrepancies can seemingly be explained by fundamental differences in testing protocols. Vetter et al. [10,11] used a well-lit arena where the speakers were easily visible and activated the sound as fish approached them, possibly facilitating a learning response to visual cues associated with sound (the speakers). Carp have excellent visual acuity and are likely capable of quickly learning visual cues when they are associated with sound. Notably, Vetter et al. [10,11] also did not measure fish tracks but rather changes in apparent lateral position of the centroid of entire groups and thus were unable to compare movements to sound pressure level or particle motion. Explicit tests of how fishes use sound with and without visual cues appear warranted.

This study also provides new information on acoustic behavior of the common carp, which is highly invasive in shallow water ecosystems. Common carp were similarly, albeit less responsive to complex sound than bighead and silver carp, as has been noted previously [55]. All three species exhibited a similar tendency to move parallel to the particle acceleration vectors out to a distance of 60 cm from the speaker. Zielinski et al. [33] also found consistent avoidance responses of all three species to a bubble curtain (a low frequency sound source). Although common carp are not reasonable surrogate for all aspects of bighead and silver carp invasions, they could be a conservative model for bigheaded carp (which are more difficult to capture and study) when testing acoustic deterrents because it is less sensitive and more readily available in areas not yet invaded by bighead or silver carp (i.e., headwaters of the Mississippi River).

The findings of this study strongly support the possibility that acoustic deterrents could be useful to help control silver, bighead, and common carp movement in rivers including the Mississippi River which is extremely turbid [56]. While earlier studies show general movement away from a sound source [10,11,37,38], our study clearly shows that particle motion is used for orientation and could be used to direct all species of carp away from an area. Nevertheless, carp barrier design should consider the fact that particle motion attenuates rapidly. One way to use this new understanding of the role of particle motion in darkness may be to design new types of acoustic deterrents to divert (vs. block) carp to swim along alternative paths (i.e. via an air curtain deflection screen; [33,57]). Acoustic deterrents have been effectively paired with bubble curtains to manipulate the distribution of sound, creating a sharp sound pressure gradient [34–36,57]. Nestler et al. [58] also proposed using directional transducers to create well defined sound fields to obstruct fish passage into water intake structures. Another possibility might be to employ lights and / or visual landmarks to provide additional information for orientation but this may not always be possible in river waters which often have poor clarity. New sounds and associated sets of stimuli warrant systematic study to see if improvement on the paradigm we tested might be possible.

Conclusions

Behavioral responses of silver, bighead, and common carp to a stationary complex sound were observed to characterize whether and how these species avoid sound in the absence of visual cues. Plotting showed all three species exhibit an oriented avoidance response which habituated after two trials. Swimming trajectories correlated strongly with the axes of local particle motion by trending towards 0°. Fish also turned away from the speaker at a distance of 20–30 cm where the sound pressure level was above 140 dB (ref. 1 μPa). Future studies should examine how carp accomplish this type of orientation, how common it might be, and whether and how other sensory cues might enhance orientation capability. The findings of this study nevertheless suggest that acoustic deterrents could be used to control invasive carp, but that field testing is needed to address issues including range, the roles of other sensory stimuli in different environments, habituation, and non-target effects, especially in low light environments. Different sounds might also be considered.

Supporting information

S1 Fig. The power spectra of (A) the sound pressure measures in the tank and (B) signal played during experiments. The sound pressure level was measured 5 cm in front of the speaker.
(TIF)

S2 Fig. Plan view of sound pressure level in dB (ref 1 μPa) at 2000 Hz in the entire enclosure at a depth of 15 cm from the tank bottom. The speaker is hidden behind a plastic screen and located at 0 cm on the X-axis, with the center of the projector face 15 cm from the tank bottom.
(TIF)

S3 Fig. Sound pressure level in dB (ref 1 μPa) at 2000 Hz as a function of radial distance from the source. Measurements plotted along radius at π/4, π/2, and 3π/4. The box in the center of enclosure causes the break in measurements along π/2 radius. Theoretical attenuation (dashed line) for shallow water is calculated using Eq. 12–13 from Akamatsu et al. [53].
(TIF)

S4 Fig. Particle acceleration in X-, Y-, and Z- direction in dB (ref 1 cms^{-2}) as a function of radial distance from the source along the enclosure centerline. Box in the center of enclosure causes the break in measurements.
(TIF)

S5 Fig. Time-series plot of mean distance between (A) common carp, (B) silver carp, and (C) bighead carp and active speaker during first playback. Open gray circles denote raw positions while black squares are the mean distance with standard error bars. The x axis shows sound starting from o when the sounds was turned on. Note that fish maintained a relative constant distance from the speaker after 30 seconds.
(TIF)

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References

1. Schuijf A. Directional hearing of cod (*Gadus morhua*) under approximate free field conditions. J. Comp. Physiol. 1975; 98: 307–332.
2. Schuijf A, Hawkins AD. Acoustic distance discrimination by the cod. Nature 1983; 302:143–144.
3. Lu Z, Popper AN. Neural response directionality correlates of hair cell orientation in a teleost fish. J. Comp. Physiol. [A] 2001; 187:453–465.
4. Popper AN, Fay RR. Rethinking sound detection by fishes. Hearing Res. 2011; 273:25–36.
5. Coombs S, Conley RA. Dipole source localization by mottled sculpin. I. Approach strategies. J. Comp. Physiol. [A] 1997; 180:387–399.
6. Coombs S, Conley RA. Dipole source localization by mottled sculpin. II. The role of lateral line excitation patterns. J. Comp. Physiol. [A] 1997; 180:401–415.
7. Zeddies DG, Fay RR, Alderks PW, Shaub KS, Sisneros JA. Sound source localization by the plainfin midshipman fish, *Porichthys notatus*. J. Acoust. Soc. Am. 2010; 127:3104–3113. https://doi.org/10.1121/1.3365261 PMID: 21117759
8. Zeddies DG, Fay RR, Gray MD, Alderks PW, Acob A, Sisneros JA. Local acoustic particle motion guides sound-source localization behavior in the plainfin midshipman fish, *Porichthys notatus*. J. Exp. Biol. 2012; 215:152–160. https://doi.org/10.1242/jeb.064998 PMID: 22162863
9. Coffin AB, Zeddies DG, Fay RR, Brown AD, Alderks PW, Bhandiwad AA, et al. Use of the swim bladder and lateral line in near-field sound source localization by fish. J. Exp. Biol. 2014; 217:2078–2088. https://doi.org/10.1242/jeb.093831 PMID: 24675557
10. Vetter BJ, Cupp AR, Fredricks KT, Gaikowski MP, Mensinger AF. Acoustical deterrence of Silver Carp (*Hypophthalmicthys molitrix*). Biol. Inv. 2015; 1–10. https://doi.org/10.1007/s10530-015-0964-6
11. Vetter BJ, Murchy KA, Cupp AR, Amberg JJ, Gaikowski MP, Mensinger AF. Acoustic deterrence of bighead carp (*Hypophthalmichthys nobilis*) to a broadband sound stimulus. J. Great Lakes Res. 2016; 1–9. https://doi.org/10.1016/j.jglr.2016.11.009
12. Plachta DT, Popper AN. Evasive responses of American shad (*Alosa sapidissima*) to ultrasonic stimuli. Acoust. Res. Lett. Online. 2003; 4:25–30.
13. Wilson M, Acolas ML, Bégout ML, Madsen PT, Wahlberg M. Allis shad (*Alosa alosa*) exhibit an intensity-graded behavioral response when exposed to ultrasound. J. Acoust. Soc. Am. 2008; 124:243–247.
14. Wilson M, Schack HB, Madsen PT, Surlykke A, Wahlberg M. Directional escape behavior in allis shad (*Alosa alosa*) exposed to ultrasonic clicks mimicking an approaching toothed whale. J. Exp. Biol. 2011; 214:22–29. https://doi.org/10.1242/jeb.043323 PMID: 21147965
15. Fay RR, Edds-Walton PL. Structures and Functions of the Auditory Nervous System of Fishes. In: Webb JF, Fay RR, Popper AN, editors. Fish Bioacoustics. New York: Springer Science+Business Media; 2008. pp. 49–97.
16. Popper AN, Fay RR. Sound detection and processing by fish: critical review and major research questions. Brain Behav. Evol. 1993; 41:14–38. PMID: 8431753
17. Higgs DM, Lu Z, Mann DA. Hearing and mechanoreception. In: Evens DH, Claiborne JB, editors. The Physiology of Fishes. Boca Raton: Taylor & Francis Group; 2006. pp. 389–428.

18. Braun CB, Grande T. Evolution of peripheral mechanisms for the enhancement of sound reception. In: Webb JF, Fay RR, Popper AN, editors. Fish Bioacoustics. New York: Springer Science+Business Media; 2008. pp. 99–144.

19. Webb JJ, Montgomery JC, Mogdans J. Bioacoustics and the lateral line system of fishes. In: Webb JF, Fay RR, Popper AN, editors. New York: Springer Science+Business Media; 2008. pp. 145–183.

20. Higgs DM, Radford CA. The contribution of the lateral line to "hearing" in fish. J. Exp. Biol. 2013; 216:1484–90. https://doi.org/10.1242/jeb.078816 PMID: 23264489

21. Schrank SJ, Guy CS, Fairchild JF. Competitive interactions between age-0 Bighead Carp and Paddlefish. Trans. Am. Fish. Soc. 2013; 132:1222–1228.

22. Irons KS, Sass GG, McClelland MA, Stafford JD. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA Is this evidence for competition and reduced fitness. J Fish Biol. 2007; 71:258–273.

23. Sampson SJ, Chick JH, Pegg MA. Diet overlap among two Asian carp and three native fishes in backwater lakes on the Illinois and Mississippi rivers. Biol. Inv. 2009; 11:483–496.

24. Sass GG, Hinz C, Erickson AC, McClelland NN, McClelland MA, Epifanio JM. Invasive bighead and silver carp effects on zooplankton communities in the Illinois River, Illinois, USA. J. Great Lakes Res. 2014; 40:911–921.

25. ACRCC (Asian Carp Regional Coordinating Committee). Asian carp control strategy framework. Council on Environmental Quality, Washington, D.C. 2014.

26. Balon EK. Origin and domestication of the wild carp, Cyprinus carpio: from Roman gourmets to the swimming flowers. Aquaculture 1995; 129:3–48.

27. Weber MJ, Brown ML. Effects of common carp on aquatic ecosystems 80 years after "carp as a dominant": ecological insights for fisheries management. Rev. Fish. Sci. 2009; 17:524–537.

28. Popper AN. Pure-tone auditory thresholds for the carp, *Cyprinis carpio*. J. Acoust. Soc. Am. 1972; 52:1714–1717.

29. Lovell JM, Findlay MM, Nedwell JR, Pegg MA. The hearing abilities of the silver carp (*Hypopthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*). Comp. Biochem. Physiol. [A] 2006; 143:286–291.

30. Ladich F, Fay RR. Auditory evoked potential audiometry in fish. Reviews in Fish Biol. Fisheries. 2013; 23:317–364.

31. Zielinski DP, Voller VR, Svendsen JC, Hondzo M, Mensinger AF, Sorensen PW. Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp. Ecol. Eng. 2014; 67:95–103.

32. Zielinski DP, Sorensen PW. Field test of a bubble curtain deterrent system for common carp. Fish. Management Eco. 2015; 22:181–184.

33. Zielinski DP, Sorensen PW. Bubble curtain deflection screen diverts the movement of both Asian and Common Carps. N. Am. J. Fish. Management. 2016; 36:267–276.

34. Pegg MA, Chick JH. Aquatic nuisance species: an evaluation of barriers for preventing the spread of Bighead and Silver carp to the Great Lakes. Final report for the Illinois-Indiana Sea Grant A/SE (ANS)-01–01. Illinois-Indiana Sea Grant, Urbana, IL. 2004.

35. Taylor RM, Pegg MA, Chick JH. Response of bighead carp to a bioacoustic behavioural fish guidance system. Fish. Management Eco. 2005; 12:283–286.

36. Ruebush B, Sass G, Chick J, Stafford J. In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp. Aquat. Inv. 2012; 7:37–48.

37. Romine JG, Jensen NR, Parsley MJ, Gaugush RJ, Severson TJ, Hatton TW, et al. Response of Bighead Carp and Silver Carp to repeated water gun operation in an enclosed shallow pond. N. Am. J. Fish. Management 2015; 35:440–453.

38. Murchy KA, Cupp AR, Amberg JJ, Vetter BJ, Fredricks KT, Gaikowski MP, et al. Potential implications of acoustic stimuli as a non-physical barrier to silver carp and bighead carp. Fish. Management Eco. 2017; 24:208–216.

39. Wysocki LE, Dittami JP, Ladich F. Ship noise and cortisol secretion in European freshwater fishes. Biol. Conserv. 2006; 128:501–508.

40. Hansen A, Ghosal R, Caprio J, Claus AW, Sorensen PW. Anatomical and physiological studies of bigheaded carps demonstrate that the epibranchial organ functions as a pharyngeal taste organ. J. Exp. Biol. 2014; 217:3945–3954. https://doi.org/10.1242/jeb.107870 PMID: 25214490

41. Matsumoto T, Kawamura G. The eye of the common carp and Nile tilapia are sensitive to near-infrared. Fish. Sci. 2005; 71:350–355.

42. Knudsen FR, Enger PS, Sand O. Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. J. Fish Biol. 1992; 40:523–534.

43. Sisler SP, Sorensen PW. Common carp and goldfish discern conspecific identity using chemical cues. Behaviour 2008; 145:1409–1425.

44. Huntingford FA, Andrew G, Mackenzie S, Morera D, Coyle SM, Pilarczk Kadri S. Coping strategies in a strongly schooling fish, the Common Carp *Cyprinus carpio*. J. Fish Biol. 2008; 76:1576–1591.

45. Karlsen HE, Piddington RW, Enger PS, Sand O. Infrasound initiates directional fast-start escape responses in juvenile roach *Rutilus rutilus*. J Exp. Biol. 2004; 207:4185–4193. https://doi.org/10.1242/jeb.01274 PMID: 15531639

46. Conover WJ. Practical Nonparametric Statistics. New York: John Wiley & Sons; 1980.

47. Kalmijn AJ. Hydrodynamic and acoustic field detection. In: Atema J, Fay RR, Popper AN, Tavolga WN, editors. Sensory Biology of Aquatic Animals. New York: Springer-Verlag, New York; 1988. pp. 83–130.

48. Batschelet E. The Raleigh test. In: Batschelet E., editor. Circular Statistics in Biology. New York: Academic Press; 1981. pp. 54–58.

49. Colgan P. The motivational basis of fish behavior. In: Pritcher T. J., editor. Behavior of Teleost Fishes 2nd Edition. London: Chapman and Hall; 1993. pp. 31–56.

50. Standdon JR. On rate-sensitive habituation. Adaptive Behavior 1993; 1:421–436.

51. Bomford M, O'Brien PH. Sonic deterrents in animal damage control: a review of device tests and effectiveness. Wildlife Soc. Bullet. (1973–2006) 1990; 18:411–422.

52. Rogers PH, Hawkins AD, Popper AN, Fay RR, Gray MD. Parvulescu revisited: small tank acoustics for bioacousticians. In: Popper AN, Hawkins AD, editors. The Effect of Noise on Aquatic Life II. New York: Springer Science+Buisiness Media, New York; 2016. pp. 933–941.

53. Akamatsu T, Okumura T, Novarini N, Yan HY. Empirical refinements applicable to the recording of fish sounds in small tanks. J. Acoust. Soc. Am. 2002; 112:3073–3082. PMID: 12509030

54. Gray MD, Rogers PH, Popper AN, Hawkins AD, Fay RR. "Large" tank acoustics: how big is big enough? In: Popper AN, Hawkins AD, editors. The Effect of Noise on Aquatic Life II. New York: Springer Science+Business Media, New York; 2016. pp. 363–369.

55. Murchy KA, Vetter BJ, Brey MK, Amberg JJ, Gaikowski MP, Mensinger AF. Not all carp are created equal: Impacts of broadband sound on common carp swimming behavior. Proc. Meetings on Acous. 2016; 27(010032):1–9.

56. Noatch MR, Suski CD. Non-physical barriers to deter fish movements. Environ. Rev. 2012; 20:71–82.

57. Welton JS, Beaumont RC, Clarke RT, Beaumont WRC. The efficacy of air, sound and acoustic bubble screens in deflecting Atlantic salmon, *Salmo salar* L., smolts in the River Frome, UK. Fish. Management Eco. 2002; 9:11–18.

58. Nestler JM, Ploskey GR, Pickens J, Menezes J, Schilt C. Responses of blueback herring to high-frequency sound and implications for reducing entrainment at hydropower dams. N. Am. J. Fish. Management. 1992; 12:667–683.

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ORIGINAL ARTICLE

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Swimming performance of adult bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845) and silver carp *H. molitrix* (Valenciennes, 1844)

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Summary

Although the movement of invasive bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*) in the Upper Mississippi River system is dependent on their ability to swim through its numerous lock-and-dams, the swimming performance of adults of these species is at present unknown. Using a large (2,935-L) mobile swim tunnel, the swimming performance of adult bighead and adult silver carp was quantified at water velocities that challenged them to exhibit either prolonged and/or burst swimming (76–244 cm/s) with fatigue times of less than 10 min. Simple log-linear models best described the relative swim speed to fatigue relationships for both species. Under these conditions, the swimming performances of adult bighead and silver carp were similar to several species of adult fishes native to the Mississippi River system, but relatively low (<3 total body lengths per second, TL/s) compared to previously studied juveniles and sub-adult bigheaded carps (3–15 TL/s). The decline in endurance with water velocity was three times greater in bighead carp (slope = −2.98) than in silver carp (slope = −1.01) and the predictive ability of the bighead model was appreciably better than the silver carp model. The differences in adult swimming performance between the two species were coincident with behavioral differences (e.g. breaching in silver carp but not in bighead carp). The swimming performance data of adult bighead and silver carp can now be used to evaluate whether their passage through man-made river structures including the gates of lock-and-dams in the Upper Mississippi River might be reduced.

1 | INTRODUCTION

Bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*), collectively referred to as bigheaded carp, comprise one of the most invasive fish taxa introduced into European and North American inland waters (Savini et al., 2010; USFWS, 2012). In the United States, both species have spread rapidly throughout the Lower and Middle Mississippi River since being introduced in the 1970s, and if left unchecked could have adverse ecological and economic impacts in the Upper Mississippi River and Great Lakes (Sass et al., 2014; Schrank, Guy, & Fairchild, 2003). The current range of bigheaded carp extends as far north as Pool 18 near Burlington, Iowa in the Mississippi River and Dresden Island Pool near Morris, Illinois in the Illinois River (USFWS, 2014). The 29 navigational lock-and-dam structures in the Mississippi River are already known to inhibit passage of native migratory fish (Knights, Vallazza, Zigler, & Dewey, 2002; Zigler, Dewey, Knights, Runstrom, & Steingraeber, 2003, 2004) and may also restrict movement of bigheaded carp by producing velocities through the gates that exceed the swimming abilities of these fish. To date, management decisions in the Mississippi River to control bigheaded carp passage have conservatively assumed that bigheaded carp swimming performance is in the same category as Pacific salmonids (*Oncorhynchus* spp.), based on their size and leaping ability (Stanley Consultants, 2011). If true, bigheaded carp should be readily passing through most dams; however, the apparent rarity of bigheaded carp in the upper reaches of the Mississippi River and Illinois River suggests otherwise. The objective of this swim tunnel study was to address the knowledge gap between the presumed and actual swimming performance of adult bigheaded carps.

Fish swimming performance is often categorized by one of three modes: sustained, prolonged, and burst swimming (Beamish, 1978). Sustained swimming is aerobically fueled and can be maintained for indefinite periods of time (typically more than 200 min), albeit at slow speeds. Burst swimming is anaerobically fueled and while fast, is brief (<30 s). Prolonged swimming is the transition between sustained and burst swimming that is partly aerobic and partly anaerobic, and can be maintained for moderate periods of time (1–200 min). Depending on the species, prolonged swimming may not be distinguishable from burst swimming. Both burst and prolonged swimming ultimately cause fish to fatigue, which limits their endurance and terminates in exhaustion (inability to swim). All of these characteristics vary greatly by species (muscle type, body morphology) and size, as well as numerous other abiotic and biotic factors. The range of velocities through a typical gated spillway in a Mississippi River lock-and-dam is thought to be approximately 1.5–5 m/s (i.e. 2–7 total body lengths per second, TL/s in large fish) and extend as far as 35 m downstream from the gates (Markussen & Wilhelms, 1987; Zigler et al., 2004), which would likely require fish to employ prolonged and burst swim speeds to pass. Accordingly, quantifying the swimming performance of adult bigheaded carp at prolonged and burst swimming speeds would be useful to understanding whether, how, and when fish can pass lock-and-dams and how this might be managed.

Both bighead and silver carp employ carangiform locomotion (Breder, 1926), a type of swimming in which body and caudal fin undulations across a third-to-half of their body length generates forward thrust that typically translates to higher burst swimming speeds than those seen in more undulatory swimmers (Sfakiotakis, Lane, & Davies, 1999). Both adult bighead and silver carp typically spend the majority of their time in slow moving waters although they seem to spawn in more turbulent areas (Calkins, Tripp, & Garvey, 2012; DeGrandchamp, Garvey, & Csoboth, 2007). Hoover, Southern, Katzenmeyer, and Hahn (2012) examined the swimming performance of juvenile and sub-adult bigheaded carps and observed that bighead carp swim speeds exceed those of silver carp across a range of sizes (TL 36–334 mm), despite having a less streamlined morphology. However, adult bigheaded carp can reach sizes four times the size of the small fish that Hoover et al. (2012) studied [i.e. up to 1,350 mm TL for bighead (Schrank & Guy, 2002) and 900 mm TL for silver carp (Seibert et al., 2015)], and swimming performance data cannot be extrapolated from small fish to large fish because swim speeds relative to total length typically change with size (Videler & Wardle, 1991). The exact relationship between relative swimming speed and size for both adult bighead and adult silver carp is currently unknown.

Swimming performance of fish is typically determined using laboratory swim tunnels in which fish are exposed to a range of water velocities so that endurance (time-to-fatigue) can be determined (Brett, 1964). Tests conducted in the field with mobile swim tunnels are advantageous because they minimize confounding influences from acclimatization, laboratory conditions, and water quality (Ellerby & Herskin, 2013). Although rarely used because of their high expense, mobile swim tunnels have been effective at measuring swim speeds for a variety of large riverine and marine fishes (Farrell et al., 2003; Graham, DeWar, Lai, Lowell, & Arce, 1990; Jones, Kiceniuk, & Bamford, 1974; Schmulbach, Tunnink, & Zittel, 1982). For the present experiments with large adult bigheaded carps, a custom-built 2,935-L mobile swim tunnel was used to test fish in the field. Similar in concept to a previously built 1,200-L laboratory swim tunnel (Hoover, Collins, Boysen, Katzenmeyer, & Killgore, 2011), this new swim tunnel was portable and larger than a 2,400-L ocean-going tunnel used for sharks (Graham et al., 1990), perhaps making it the largest ever used.

The study was designed to allow for direct comparisons of swimming performance and behavior of adult bighead and adult silver carp at prolonged and burst swim speeds to explore the possibility of hydraulic containment of invasive bigheaded carp at lock-and-dam structures. Specific objectives included determining: (i) the swimming performances of the adult bighead and silver carp and whether these species have different swimming abilities; (ii) if, and to what extent, body length, gender, and water temperature influence carp swimming performance; and (iii) how bigheaded carp swimming performance compares with that of fish native to the Mississippi River system as well as smaller conspecifics, and how that understanding might then lead to the possibility of managing the spread of these invasive carps.

2 | MATERIALS AND METHODS

2.1 | Test apparatus

Swim tests were conducted in a specially designed 2,935-L mobile Brett-type swim tunnel (Fig. 1). The tunnel was mounted on a 5.5 × 2.0 m trailer and pulled with a truck so that fish could be tested near their point of capture. The trailer was equipped with four leveling jacks, which enabled the vertical position of the tunnel to be adjusted. A 10 horsepower Varidrive US Electrical Motor, capable of 1,740 rpm, 678 ***g*** centrifugal force, drove a stainless steel shaft attached to a

FIGURE 1 Mobile swim tunnel with adult bighead carp *Hypophthalmichthys nobilis* inside

40 cm diameter (40 cm pitch), three-blade propeller, which provided thrust. The motor could be run at shaft speeds of 50–750 rpm and direction of flow could be reversed. The tunnel was made from thermoplastic components, principally Lexan, reinforced with stainless steel frames and perimeters. Components consisted of a 2,029-L test chamber (2.4 m L × 0.9 m W × 0.9 m H), and a 44 cm diameter, 907-L, circulation tube that received outflow from the rear of the tank and propelled it back into the front of the tank as inflow. The propeller was housed in the bottom of the circulation tube and could be viewed through a polycarbonate window. A hinged lid was attached along the length of the tank and secured using pivoting aluminum lock-downs at each end while C-clamps were used to tightly seal the lid against a gasket along the top edges of the tank and minimize water loss. Polycarbonate grids with pores (1.3–5.0 cm) functioned as collimators (flow filters) reducing turbulence, and were positioned at the front and rear ends of the tank. Slots positioned 30 cm from the inflow and outflow ports allowed additional collimators to be inserted to further reduce turbulence, but restricted the working section to 1,525-L. The working section of tank could be used with or without a polycarbonate box that created boundary-layer flow along the bottom and reduced waves at the surface. This box was a double platform with a lower platform (false bottom) and upper platform (false top), having the same footprint as the working section of the tank. Spacers attached to the lower platform elevated it 23 cm off the bottom and submerged the upper platform 23 cm below the lid. The false top and bottom created a functional working section volume of 934-L.

The tunnel was calibrated three times corresponding to its three test configurations with no insert, a false bottom and top, and false bottom only (see below). Velocity was measured in the middle of the tank at three vertical positions (20% from surface, 50% from surface, and 80% from surface), at three distances along the length of the tank (at inflow, 1 m from inflow, at outflow), resulting in nine points for each velocity and 72 points for each configuration for each of eight motor speeds (50–700 rpm). At each point 5–10 measurements were taken using a Marsh-McBirney Flo-Mate 2000 with the probe mounted on a wading rod. All measurements were taken with the tunnel lid closed and the tank filled to the lid. Because values for the mid-length vertical profile were intermediate between those of the inflow and outflow profiles and were more uniform, they were averaged and the mean value was used. Simple linear regressions were performed with motor speed as independent variable and mean water velocity as dependent variable resulting in the following rating curves:

$$\text{Velocity}_{\text{No Insert}} = 0.3279\ [\text{rpm}],\ R^2 = .9982$$
$$\text{Velocity}_{\text{False Top and Bottom}} = 0.3329\ [\text{rpm}],\ R^2 = .9973$$
$$\text{Velocity}_{\text{False Bottom Only}} = 0.3052\ [\text{rpm}],\ R^2 = .9950$$

2.2 | Study site and field collection

This study took place at Forest Home Chute (32°45.340′N; 91°01.440′W), Warren County, Mississippi (Pongruktham, Ochs, & Hoover, 2010), a long, narrow river scar that parallels the main channel of the Mississippi River just north of river km 724–729. At low river stages, it functions as a backwater lake and at high river stages as a secondary channel. The reach of Forest Home Chute sampled is 3.5 km long and is the middle section of the chute. More than 20 species of fish have been documented from the middle reach and both bighead and silver carps are significant components of the fish community (Varble et al., 2007). We tested fish in the spring (17–31 March 2015) and summer (04–19 June 2015). Water was moderately conductive (373 ± 26 and 385 ± 8 µS, respectively), slightly alkaline (7.76 ± 0.26, 8.30 ± 0.36 pH), and normoxic (10.6 ± 2.3, 9.2 ± 1.7 mg/L). Turbidity was higher and water temperature lower in March (24.1 ± 15.8 NTU, 12.1 ± 1.4°C) than in June (5.0 ± 1.9 NTU; 27.5 ± 0.9°C). Channel depth was 7–10 m in March, 5–6 m in June.

The test fish were collected in Forest Home Chute and transported to the swim tunnel, which was located on shore. Carp were collected each sampling period by a commercial fisherman using wide-mesh (7.5–12.5 cm) surface gillnets of variable length. Surface gillnets were used to avoid hypoxia at greater depths. Gillnets were monitored during sets and every 30 min thereafter. Time of capture was noted for each fish while being removed from the netting, then lifted into the boat and placed in an aerated 350-L live-well filled with fresh river water and immediately taken to shore. Fish were removed by hand from the live-well, wrapped in a soft nylon body sling, hand-carried to the swim tunnel, and immediately placed in the tank by unrolling the sling underwater. If more than one fish was caught, 1–2 representatives were selected for later tests, tethered in shady water using waxed nylon twine looped snugly around the caudal peduncle. If more than three fish were caught, all extra fish were immediately released. Average time from capture to testing was 49.3 min for bighead carp and 62.0 min for silver carp.

The swim tunnel was operated at a single shoreline position approx. 30 m distant from the water's edge. Prior to tests each morning, the tunnel was filled with untreated well water that was circulated at 35 cm/s, treated with API Stress Coat (Mars Fishcare North America, Inc., Chalfont, PA), and aerated with compressed oxygen. Throughout each day of testing, water was partially exchanged and re-aerated to maintain normoxia (>7.00 mg/L), pH (>7.3), and clarity (<5 NTU). Test temperatures varied daily and throughout the day during each period but were cooler in March (13.1–19.3°C) than in June (20.8–25.9°C). After completion of tests each evening, the tunnel was drained.

2.3 | Testing

Adult carp of both species were tested over a range of constant water velocities (75–244 cm/s) with several replicates for each water velocity. For a test, a freshly captured carp was carefully placed into the working section of the swim tunnel and allowed to habituate to a water velocity of 7 cm/s for 10 min, then 28 cm/s for another 10 min, and lastly 42 cm/s for another 10 min. At the end of the habituation period, water velocity was increased over a 2–3 s interval to one of 12 test velocities (76–244 cm/s), and the fish was observed until it fatigued. Each fish was tested only once. During testing, three aspects of swimming were evaluated: (i) rheotaxis—head-first orientation into the direction of water flow, (ii) endurance (or time-to-fatigue)—length of time that a fish was able to maintain a position in flowing water, (iii) behavior—mode of locomotion used to swim forward or maintain station. If a fish failed to exhibit rheotaxis, it was given 1–2 min rest before flow was again increased to the test velocity, but if after multiple attempts it still did not exhibit rheotaxis, or if it exhibited behavior atypical for the species, it was considered a "non-performer". Most fish, however, were performers and trials lasted until the fish was exhausted (i.e. became impinged on the downstream grid twice) or 60 min had passed. If exhausted, flow was reversed for 10 s, and the fish was allowed to re-orient for 10 min at 7 cm/s. If the fish was unable to continue swimming, the test was ended and the time of initial impingement recorded. If the fish resumed swimming, the test was restarted and continued until the fish was impinged a second time and unable to extricate itself and the time was then recorded as the endpoint. If the second time-to-fatigue was less than first, the original endpoint was accepted. If the second time-to-fatigue was greater than the first, the fish was classified as a "non-performer". A total of 80 adult carp were tested including 17 adult bighead carp (760–1040 mm TL, 5.2–12.3 kg, and condition factor, $K_f = 0.98–1.60$) and 63 adult silver carp (535–921 mm TL, 1.5–9.0 kg, and $K_f = 0.85–1.30$). No fish died as a result of testing. After testing, carp were euthanized with MS-222 and total length and weight recorded, as well as any morphological anomalies (e.g. scarring, missing fins, etc.). Gonads were examined to establish gender.

Initial trials (17/80) at slower speeds were successful without the box insert, but at higher motor speeds (≥600 rpm) surface and bottom velocity shadows, or "dead zones", were found near the inflow and adjustments were made. Subsequent trials (60/80) were conducted using only the false bottom insert, which reduced dead zones while promoting consistent normal behavior and post-test recovery, although three trials also used the false top insert. Black plastic sheeting overlaid on the surface of the lid promoted relaxed swimming and eliminated strikes against the tank lid by leaping silver carp.

2.4 | Data analysis

Test speeds, in cm/s, were converted into relative swim speeds, in total lengths/second (TL/s), by dividing absolute water velocity by total length of fish. Endurance (time to fatigue) was transformed using natural logarithm. Data were compiled and analyzed in SAS® 9.3 using General Linear Models (SAS Institute, Cary, NC). Non-performers, fish that exhibited conspicuous stress, trials with equipment failure, and fish that did not fatigue were excluded from analyses.

To relate swimming endurance to swim speed (water velocity), we developed three performance models for each species: broken-stick, log-linear (sensu Castro-Santos, 2005), and log-linear plus temperature (sensu Peake, Beamish, McKinley, Scruton, & Katapodis, 1997). The broken-stick model assumed that prolonged and burst swim speeds are discrete responses represented by two different lines with an inflection point and distinct slopes at slower and faster ranges of swim speed. The log-linear model assumed that prolonged and burst speeds are a graded continuous response represented by a single line with no significant inflection or change in slope at slower and faster ranges of swim speed. Evidence for a mode shift between prolonged and burst swimming in the broken stick model was tested using the model:

$$\mathrm{Ln}[\mathrm{Endurance}] = \beta 0 + \beta 1\,[\mathrm{TL/s}] + \beta 2\,[x1] + \beta 3\,[x1]\,[\mathrm{TL/s}],$$

in which the first and second terms represent the intercept and slope for a line for prolonged swimming, while the third and fourth terms are the adjustment to the intercept and slope for a separate line for burst swimming. For swim speeds considered prolonged, $x1 = 0$; for burst speeds $x1 = 1$. The model was run iteratively, incrementing maximum prolonged swim speed by 0.01 TL/s. The log-linear model followed the form:

$$\mathrm{Ln}[\mathrm{Endurance}] = \beta 0 + \beta 1\,[\mathrm{TL/s}].$$

A third type of model, which evaluated the influence of water temperature on the log-linear model followed the form:

$$\mathrm{Ln}[\mathrm{Endurance}] = \beta 0 + \beta 1\,[\mathrm{TL/s}] + \beta 2\,[\mathrm{TEMP}].$$

For all three models, fit of model residuals to a normal distribution was tested using Shapiro-Wilks statistic for which $W > 0.95$ indicates high fit, $W = 0.90–95$ indicates a good fit, and $W < 0.90$, a poor fit. Magnitude of W is generally considered a more reliable indicator of fit than tests of significance, which can be strongly influenced by minor departures of kurtosis and skew (Douglass & Douglass, 2004). Predictive power of the respective models, and individual regression coefficients within each of those models, were quantified as R^2 and p values. Model selection was based on the corrected version of the Akaike Information Criterion (AICC) to select the most parsimonious model (Castro-Santos, 2005). Analysis of covariance (ANCOVA) was used to compare log-linear model coefficients between bighead and silver carp.

Once bighead and silver carp data were evaluated, their swimming performance was qualitatively compared with other river fish and juveniles of the same species. First, swim tunnel data were tabulated for other comparably sized Mississippi River fishes including lake sturgeon (*Acipenser fulvescens*), shovelnose sturgeon (*Scaphirhynchus platorynchus*), and smallmouth buffalo (*Ictiobus bubalus*). Swim tunnel data of large (>500 mm TL) sockeye salmon (*Oncorhynchus nerka*) were also tabulated to address the assumption that Pacific salmonids may be used as models for estimating bigheaded carp swimming performance. Second, to evaluate the influence of fish size on swimming performance, endurance data for sizes classes of bigheaded carp previously studied (Hoover et al., 2012) were plotted with the adult carp data from this study. Data were plotted using total length as the independent variable and relative swim speed (TL/s) as the dependent variable. Juvenile carp swim speed values were calculated by dividing the limits for prolonged (1 min) and burst (0.1 min) swimming modes by the range of fish lengths tested (e.g. for a given TL there are two swim speed data points).

3 | RESULTS

All 17 adult bighead carp were performers that exhibited typical and regular swimming movements and their data were used in analyses.

Swimming behavior was dominated by free-swimming in the water column with brief bouts of occasional tail-bracing observed prior to fatigue. The log-linear model fit the bighead carp data best and was a slightly better fit than the broken-stick model for which the mode shift and interaction term were both non-significant, making the model less informative (AICC = 59.40) than the simpler log-linear model (AICC = 55.90; Table 1). The slope of the swim speed to fatigue line was −2.98 and had low point scatter (R^2 = .78) for the log-linear model. Adding water temperature as a co-variate to the log-linear model increased R^2 by 7% but was less informative (AICC = 58.66) than the log-linear model. Residuals for both log-linear and log-linear plus temperature models were distributed normally (*W* > 0.95). Estimators of water temperature for bighead carp were negative, indicating that endurance was higher at cooler temperatures. For bighead carp, 94% (16/17) of all observations were within the prediction limits of the log-linear model; males and females were equitably distributed above, on, and below the regression line; and data for warm water tests predominated (6/9) below the line, supporting a negative effect of temperature on endurance (Fig. 2).

For adult silver carp, 43 of 63 individuals performed while exhibiting typical and regular swimming movements and were used in the analyses. Of fish included, swimming behavior was again characterized by free-swimming in the water column with brief bouts of occasional tail-bracing observed prior to fatigue. The broken-stick model was significant and slightly more informative (AICC = 126.85) than the simpler log-linear model (AICC = 129.77; Table 1), but the slope of the burst speed line was slightly positive, thus the log-linear model was considered the best. The slope of the swim speed to fatigue line was three times less than bighead carp at −1.01 for the log-linear model (ANCOVA: *F* = 14.34, *p* < .001). The point scatter was greater for silver carp (R^2 = .19), which indicated greater predictive power of the bighead carp log-linear model. Adding water temperature as a co-variate to the log-linear model increased R^2 by 9% but was less informative (AICC = 131.90) than the log-linear model. Residuals for both log-linear and log-linear plus temperature models were normally distributed (*W* > 0.95). Estimators of water temperature for silver carp were negative, indicating that endurance was also higher at cooler

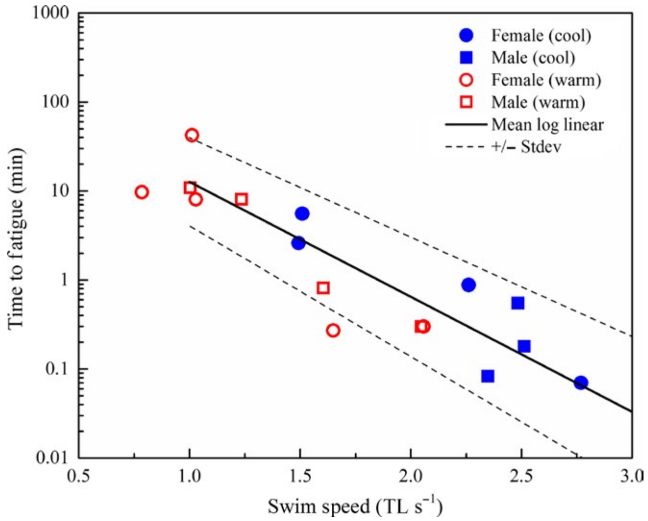

FIGURE 2 Log-linear model for bighead carp *H. nobilis* (*n* = 17) swimming performance. Boundaries on model are means ± *SE*. Individual data points coded to indicate water temperature (blue = cool water [13.1–19.3°C], red = warm water [20.8–25.9°C]), and gender (○ for female, □ for male)

TABLE 1 Broken-stick, log-linear, and log-linear plus temperature models for swimming endurance of adult bighead and silver carp

Species	Model	Effect	Estimate	Standard Error	*df*	*t*-, *F* value	Pr > *t*, *F*	R^2	Pr > *t*,*F*	AICC
Bighead carp	Broken-stick	β0	6.746	1.179	13	5.72	<0.0001	.809	<0.0001	59.40
		β1	−3.981	0.865		−4.60	0.0005			
		β2	−3.178	4.708		−0.68	0.5114			
		β3	1.889	2.075		0.91	0.3794			
	Log-linear	β0	5.521	0.733	15	7.53	<0.0001	.782	<0.0001	55.99
		β1	−2.978	0.406		−7.34	<0.0001			
	Log-linear + temperature	β0	9.139	1.569	13	5.83	<0.0001	.850	<0.0001	58.66
		β1	−3.479	0.401		−8.67	<0.0001			
		β2	−0.137	0.054		−2.52	0.0246			
Silver carp	Broken-stick	β0	3.583	1.221	39	2.93	0.0056	.282	0.0044	126.85
		β1	−2.061	0.749		−2.75	0.0090			
		β2	−6.429	3.061		−2.10	0.0422			
		β3	3.009	1.370		2.20	0.0341			
	Log-linear	β0	1.916	0.654	41	2.93	0.0055	.192	0.0033	129.77
		β1	−1.015	0.325		−3.12	0.0033			
	Log-linear + temperature	β0	4.009	1.104	39	3.63	0.0008	.286	0.0012	131.90
		β1	−1.193	0.319		−3.74	0.0006			
		β2	−0.088	0.038		−2.30	0.0270			

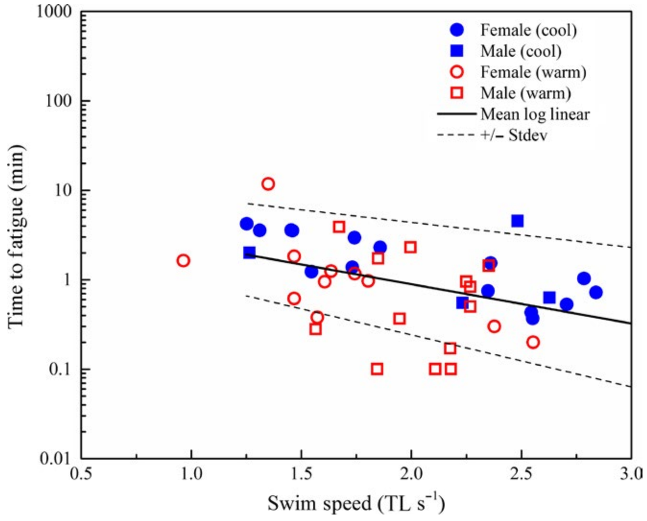

FIGURE 3 Log-linear model for silver carp *H. molitrix* (*n* = 43) swimming performance. Boundaries on model are means ± *SE*. Individual data points coded to indicate water temperature (blue = cool water [13.1–19.3°C], red = warm water [20.8–25.9°C]) and gender (○ for female, □ for male)

temperatures (Fig. 3). For silver carp, 79% (34/43) of observations were within prediction limits of the model; females and males were equally distributed above, on, and below the regression line; warm water tests again predominated (14/24) below the line, indicating a possible negative effect of warm water temperature on endurance (Fig. 3). Exclusion of 20 silver carp from the analysis was due to non-performance (8/20), conspicuous stress (7/20), equipment failure (1/20), and lack of fatigue (4/20). Notably, all four silver carp that did not fatigue (trials terminated after 60 min) had been tested at relatively slow speeds ranging from 76 to 107 cm/s (0.9–1.4 TL/s).

Tabulating data from fish native to the Mississippi River, adult bighead and silver carp swim speeds were greater than that of lake sturgeon but less than those of shovelnose sturgeon and smallmouth buffalo (Table 2). Bigheaded carp swim speeds were less than half the swim speeds of sockeye salmon at the same endurance times (Table 2).

When adult bighead and silver data from this study were combined with data from juvenile bigheaded carps previously tested, a power-law decay (with exponents of −0.56 and −0.63) could be fit to describe the reduction in relative swim speed with size (Fig. 4). Swim speeds declined from approx. 3–15 TL/s for juvenile bighead carp to 1–3 TL/s for adults. Similarly, swim speeds declined from approx. 3–9 TL/s for juvenile silver carp to 1–3 TL/s for adults. Across the size range of adult carp of both species, the response of relative swim speed to length was asymptotic.

4 | DISCUSSION

Adult bighead and silver carp exhibited regular and typical swimming movements in a large outdoor swim tunnel. While adult bighead carp showed an ability to swim for about 1 min at 1.85 TL/s (168 cm/s) and about 0.5 min at 2.09 TL/s (189 cm/s), adult silver carp swam about 1 min at 1.89 TL/s (151 cm/s) and about 0.5 min at 2.57 TL/s (206 cm/s). These swim speeds are comparable to three fish species native to the Mississippi River, but far lower in magnitude than those for sockeye salmon (Table 2). Thus Pacific salmonids are poor models for bigheaded carp swimming abilities. Differences between adult bighead and silver carp were evident. The bighead carp had a more pronounced decline in endurance with increasing water velocity than did silver carp. The swimming performance of adult bighead carp was also less variable than that of silver carp. This is consistent with field observations of brief high burst speeds and occasional breaching by silver carp as well as morphological variation (Parsons, Stell, & Hoover, 2016). Together, these swim performance data could be used to evaluate if and how adult bighead and silver carp swim through spillway gates in the Mississippi River lock-and-dams and whether changes to gate operation could hydraulically contain both species.

Log-linear models of both bighead and silver carp best fit our data. Although water temperature was a statistically significant covariate, it provided only marginal improvement in the overall model for bighead and silver carp. The log-linear models were similar in form (low slope,

TABLE 2 Predicted water velocities corresponding to three different endurance times based on swimming performance models for species of similar sizes

		Water Velocity for Endurance (TL/s)			
Species	Mean Total Length (mm)	>10 min	1 min	0.5 min	Reference
Bighead carp	908	1.08	1.85	2.09	This study
Silver carp	801	<1.25	1.89	2.57	This study
Lake sturgeon[a]	1,200	1.03	1.31	1.39	Peake et al. (1997)
Shovelnose sturgeon[b]	579	1.77	NA	NA	Hoover et al. (2011)
Smallmouth buffalo[b]	311	2.00	NA	NA	Schmulbach et al. (1982)
Sockeye salmon[c]	541	3.98	4.25	>4.25	Brett (1982)

[a] Data for lake sturgeon derived from a model that used multiple-regression between water velocity, water temperature, and time-to-fatigue at a water temperature of 14°C.

[b] Data for shovelnose sturgeon and smallmouth buffalo are mean 15 min critical swim speeds (i.e. maximum cumulative water velocity at which swimming for 15 min was predicted).

[c] Data for sockeye salmon based on a log-linear relationship between water velocity and time-to-fatigue at a water temperature of 18°C.

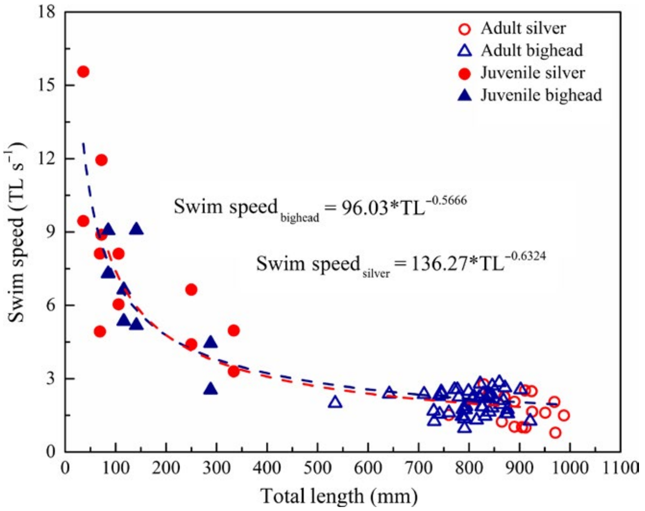

FIGURE 4 Relationship of swim speed (TL/s) to total length for juvenile, sub-adult (Hoover et al., 2012), and adult silver (*n* = 43) and bighead carp (*n* = 17). Equation and correlation of least squares for each line are provided

moderate point scatter) to those developed for other species of pelagic planktivores with cruiser morphology, like alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*), but were conspicuously lower in magnitude (Castro-Santos, 2005). The measured top-end speeds of adult bigheaded carps of ~2.8 TL/s, seemingly representative of burst swimming, are well below the generally assumed maximum burst speed of 10 TL/s for fish (Videler & Wardle, 1991). It also falls well below the maximum burst speed of ~15 TL/s previously measured for small (<250 mm TL) juvenile bighead and silver carp (Hoover et al., 2012; Fig. 4). The relatively slow adult swim speeds documented in this study are counter to perceptions of bigheaded carp as powerful and swift swimmers. Although it also falls below estimates of maximum swim speeds for silver carp from a video-based study of leaping fish (Parsons et al., 2016), such high speeds can easily be accommodated by our models by extrapolating the regression line and prediction boundaries out to a time-to-fatigue less than 1 s. In sum, these data strongly suggest that the swimming performance of adult bigheaded carp is rather typical of other large river fishes.

Adult silver carp exhibited slightly higher endurances than adult bighead carp at higher swim speeds but were also more variable. Silver carp are more sensitive to stress than bighead carp and jump, perhaps explaining the much greater variation in silver carp data. In contrast, the bighead carp data were more tightly clustered. If most upstream passage occurs through the spillway gates and not through the lock chamber, as suggested by telemetry data in the Middle Mississippi River (Tripp, Brooks, Herzog, & Garvey, 2014), the fact bighead carp grow larger than silver carp and may yet obtain faster absolute swim speeds might partially explain why few, but mostly large bighead carp are at present found in the Upper Mississippi River above prominent lock-and-dams such as Lock and Dam #5 (MNDNR, 2015). Alternatively, bighead carp may have a more extensive geographic distribution upriver and are available to colonize pools whereas silver carp do not.

Experiments using large fish in enclosed swim tunnels are imperfect, but several factors suggest that our conclusion (i.e. bigheaded carps are average swimmers with relatively low endurance at burst swim speeds) is parsimonious. First, great care was taken in collecting and testing experimental fish and the largest mobile swim tunnel ever employed in the field was used. Notably, no carp died and few showed signs of stress. Second, each fish was re-evaluated after testing to verify initial trial endpoints and fatigue. Third, data from all non-performers were excluded because this would have negatively biased results. Similarly, data from fish that did not fatigue were excluded because they were tested at slow speeds that did not require prolonged or burst swimming. Lastly, several statistical models were evaluated to identify the best one.

One possible explanation for the failure of bigheaded carps to colonize pools of the Upper Mississippi River after their establishment in the Lower and Middle Mississippi River may be that they struggle to swim through the rapidly flowing waters, which pass through the numerous gates that comprise Mississippi River lock-and-dams. If true, then the upstream movement of bigheaded carp might be further impeded by adjusting gate operation, effecting a type of hydraulic containment. Existing data on fish passage and water flow, while limited, support this possibility. For example, the head differential at Lock and Dam #8 (Genoa, Wisconsin, USA) at present exceeds 1 m 90% of the year, and by our calculations generates a uniform jet of water with velocities >4.5 m/s, a swimming speed that a large 900 mm TL silver carp can only maintain for 2.5 s. Once water velocity is factored in, the distance such a large silver carp can cover is likely to be <1 m, which would be insufficient to pass through the gates at this particular structure and hydraulic condition. Although these calculations only consider flow fields directly beneath the gates, which is relatively uniform but spatially limited, flows further downstream of the gates are turbulent with eddies that may provide fish a low velocity pathway up to and possibly through the dam. However, data are very limited. Spatially and temporally detailed velocity data obtained through computational fluid dynamics models are now urgently needed to better evaluate if and how bigheaded carp might pass through the variable flows near gates of individual lock-and-dam structures under different flow regimes. This work is now underway.

Alternative pathways for carp passage such as human assisted dispersal (i.e. carp minnows used as bait; Conover, Simmonds, & Whalens, 2007), and possible passage of carps through lock chambers should be factored in. Initial fish tracking data suggest that bigheaded carp do not routinely exploit locks (Tripp et al., 2014), but further study is needed. However, if warranted, bigheaded carp passage through locks could be eventually addressed using behavioral deterrents given the relatively small size and number of such structures (Noatch & Suski, 2012; Zielinski & Sorensen, 2016). Future study should ideally address passage of native fishes. In sum, our study demonstrates that the swimming abilities of adult bigheaded carps appear rather typical of many other large river fishes and that with further study their swimming performance, and associated behaviors, could be exploited to impede the upstream invasion of this invasive genus through some Mississippi River lock-and-dams.

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REFERENCES

Beamish, F. W. H. (1978). Swimming capacity. In W. S. Hoar & J. D. Z. Randall (Eds.), *Fish physiology*, Vol. 7: Locomotion (pp. 101–187). New York, NY: Academic Press Inc. pp. 576

Breder, C. M. (1926). The locomotion of fishes. *Zoologica*, *4*, 159–256.

Brett, J. R. (1964). The respiratory metabolism and swimming performance of young sockeye salmon. *Journal of the Fisheries Research Board of Canada*, *21*, 1522–1529.

Brett, J. R. (1982). The swimming speed of adult pink salmon (*Oncorhychus gorbuscha*) at 20°C and a comparison with sockeye salmon, *O. nerka*. Can Tech. Rep. Fish. *Aquatic Sciences*, *1143*, 40.

Calkins, H. A., Tripp, S. J., & Garvey, J. E. (2012). Linking silver carp habitat selection to flow and phytoplankton in the Mississippi River. *Biological Invasions*, *14*, 949–958.

Castro-Santos, T. (2005). Optimal swim speeds for traversing velocity barriers: An analysis of volitional high-speed swimming behavior of migratory fishes. *Journal of Experimental Biology*, *208*, 421–432.

Conover, G., Simmonds, R., & Whalens, M. (Eds.) (2007). *Management and control plan for bighead, black, grass, and silver carps in the United States* (p. 223). Washington, D.C.: Asian Carp Working Group, Aquatic Nuisance Species Tash Force.

DeGrandchamp, K. L., Garvey, J. E., & Csoboth, L. A. (2007). Linking adult reproduction and larval density of invasive carp in a large river. *Transactions of the American Fisheries Society*, *136*, 1327–1334.

Douglass, L., & Douglass, S. (2004). Data: getting to know you, getting to all about you. Proceedings of the Twenty-Ninth Annual SAS® Users Group International Conference. Cary, NC. Paper 239–29.

Ellerby, D. J., & Herskin, J. (2013). Swimming flumes as a tool for studying swimming behavior and physiology: Current applications and future developments. In A. P. Palstra & J. V. Planas (Eds.), *Swimming physiology of fish* (pp. 345–375). Heidelberg, Berlin: Springer. pp. 429.

Farrell, A. P., Lee, C. G., Tierney, K., Hodaly, A., Clutterham, S., Healey, M., … Lotto, A. (2003). Field-based measurements of oxygen uptake and swimming performance with adult Pacific salmon using a mobile respirometer swim tunnel. *Journal of Fish Biology*, *62*(1), 64–84.

Graham, J. B., DeWar, H., Lai, N. C., Lowell, W. R., & Arce, S. M. (1990). Aspects of shark swimming performance determined using a large water tunnel. *Journal of Experimental Biology*, *151*(1), 175–192.

Hoover, J. J., Collins, J., Boysen, K. A., Katzenmeyer, A. W., & Killgore, K. J. (2011). Critical swimming speeds of adult shovelnose sturgeon in rectilinear and boundary-layer flow. *Journal of Applied Ichthyology*, *27*, 226–230.

Hoover, J. J., Southern, L. W., Katzenmeyer, A. W., & Hahn, N. M. (2012). Swimming performance of Bighead Carp and Silver Carp: methodology, metrics, and management applications. Aquatic Nuisance Species Research Program Technical Notes Collection 12–3, US Army Engineer Research and Development Center, Vicksburg, MS, pp. 12. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/ansrp12-3.pdf. Accessed on: 2 May 2016.

Jones, D. R., Kiceniuk, J. W., & Bamford, O. S. (1974). Evaluation of the swimming performance of several fish species from the Mackenzie River. *Journal of the Fisheries Research Board of Canada*, *31*, 1641–1647.

Knights, B. C., Vallazza, J. M., Zigler, S. J., & Dewey, M. R. (2002). Habitat and movement of lake sturgeon in the upper Mississippi River system, USA. *Transactions of the American Fisheries Society*, *131*, 507–522.

Markussen, J. V., & Wilhelms, S. C. (1987). Scour protection for lock and dams 2–10, Upper Mississippi River. Hydraulic Model Investigation (pp. 54). Technical Report HL-87-4. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

MNDNR (Minnesota Department of Natural Resources) (2015). *Invasive species of Minnesota: Annual report 2015* (pp. 64). St. Paul, MN: Minnesota Department of Natural Resources.

Noatch, M. R., & Suski, C. D. (2012). Non-physical barriers to deter fish movements. *Environmental Reviews*, *20*(1), 71–82.

Parsons, G. R., Stell, E. L., & Hoover, J. J. (2016). Estimating burst speed of silver carp (*Hypophthalmichthys molitrix*) using videography and principles of projectile physics (pp. 10). Aquatic Nuisance Species Research Program Technical Notes Collection 16-X. Vicksburg, MS: US Army Engineer Research and Development Center (In Press).

Peake, S., Beamish, F. W. H., McKinley, R. S., Scruton, D. A., & Katapodis, C. (1997). Relating swimming performance of lake sturgeon, *Acipenser fulvescens*, to fishway design. *Canadian Journal of Fisheries and Aquatic Science*, *54*, 1361–1366.

Pongruktham, O., Ochs, C., & Hoover, J. J. (2010). Observations of silver carp (*Hypophthalmichthys molitrix*) planktivory in a floodplain lake of the lower Mississippi River basin. *Journal of Freshwater Ecology*, *25*(1), 85–93.

Sass, G. G., Hinz, C., Erickson, A. C., McClelland, N. N., McClelland, M. A., & Epifanio, J. M. (2014). Invasive bighead and silver carp effects on zooplankton communities in the Illinois River, Illinois, USA. *Journal of Great Lakes Research*, *40*, 911–921.

Savini, D., Occhipinti-Ambrogu, A., Marchini, A., Tricarico, E., Gherardi, F., Olenin, S., & Gollasch, S. (2010). The top 27 animal alien species introduced into Europe for aquaculture and related activities. *Journal of Applied Ichthyology*, *26*(Suppl. 2), 1–7.

Schmulbach, J. C., Tunnink, D. H., & Zittel, A. E. (1982). *Swimming performance of fishes endemic to the Missouri River in South Dakota* (pp. 127). FWS/OBS PB83124842. Kearneysville, WV: U.S. Fish and Wildlife Service Office of Biological Services.

Schrank, S. J., & Guy, C. S. (2002). Age, growth, and gonadal characteristics of adult bighead carp, *Hypophthalmichthys nobilis*, in the lower Missouri River. *Environmental Biology of Fishes*, *64*, 443–450.

Schrank, S. J., Guy, C. S., & Fairchild, J. F. (2003). Competitive interactions between age-0 bighead carp and paddlefish. *Transactions of the American Fisheries Society*, *132*, 1222–1228.

Seibert, J. R., Phelps, Q. E., Yallaly, K. L., Tripp, S., Solomon, L., Stefanavage, T., … Taylor, M. (2015). Use of exploitation simulation models for silver carp (*Hypophthalmichthys molitrix*) populations in several Midwestern US rivers. *Management of Biological Invasions*, *6*, 295–302.

Sfakiotakis, M., Lane, D. M., & Davies, J. B. C. (1999). Review of fish swimming modes for aquatic locomotion. *IEEE Journal of Oceanic Engineering*, *24*, 237–252.

Stanley Consultants (2011). *Coon Rapids dam fish barrier and improvements preliminary design* (p. 396). St. Paul, MN: Prepared for Minnesota Department of Natural Resources.

Tripp, S., Brooks, R., Herzog, D., & Garvey, J. (2014). Patterns of fish passage in the Upper Mississippi River. *River Research and Applications*, *30*, 1056–1064.

USFWS (United States Fish and Wildlife Service) (2012). The cost of invasive species. US Fish and Wildlife Service, Washington DC (pp. 2). Retrieved from https://www.fws.gov/verobeach/PythonPDF/CostofInvasivesFactSheet.pdf. Accessed on: 2 May 2016.

USFWS (United States Fish and Wildlife Service) (2014). The first annual report to congress: summary of activities and expenditures to manage the threat of Asian carp in the Upper Mississippi and Ohio River basins, June 2012 to June 2014 (pp. 113–121). Bloomington, MN.

Varble, K., Hoover, J. J., George, S. G., Murphy, C. E., & Killgore, K. J. (2007). Floodplain wetlands as nurseries for Silver Carp, *Hypophthalmichthys molitrix*: A conceptual model for use in managing local populations. Aquatic Nuisance Species Research Program Technical Notes Collection -7-04, US Army Engineer Research and Development Center, Vicksburg, MS (pp. 14). Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/ansrp07-4.pdf

Videler, J. J., & Wardle, C. S. (1991). Fish swimming stride by stride: Speed limits and endurance. *Review in Fish Biology and Fisheries*, *1*, 23–40.

Zielinski, D. P., & Sorensen, P. W. (2016). Bubble curtain deflection screen diverts the movement of both Asian and common carp. *North American Journal of Fisheries Management*, *36*, 267–276.

Zigler, S. J., Dewey, M. R., Knights, B. C., Runstrom, A. L., & Steingraeber, M. T. (2003). Movement and habitat use by radio-tagged paddlefish in the upper Mississippi River and tributaries. *North American Journal of Fisheries Management*, *23*(1), 189–205.

Zigler, S. J., Dewey, M. R., Knights, B. C., Runstrom, A. L., & Steingraeber, M. T. (2004). Hydrologic and hydraulic factors affecting passage of paddlefish through dams in the upper Mississippi River. *Transactions of the American Fisheries Society*, *133*(1), 160–172.