**M.L. 2009 Project Abstract**
For the Period Ending June 30, 2012

**PROJECT TITLE:** Controlling the Movement of Invasive Fish Species
**PROJECT MANAGER:** Vaughan R. Voller
**AFFILIATION:** U of M, Department of Civil Engineering, SAFL
**MAILING ADDRESS:** Mississippi River at 3rd Ave S.E.
**CITY/STATE/ZIP:** Minneapolis, MN 55414
**PHONE:** 612-625-0764
**E-MAIL:** volle001@umn.edu
**WEBSITE:** http://personal.ce.umn.edu/~voller/
**FUNDING SOURCE:** Environment and Natural Resources Trust Fund
**LEGAL CITATION:** M.L. 2009, Chp.143, Sec. 2, Subd. 6d.

**APPROPRIATION AMOUNT: $300,000**

## Overall Project Outcome and Results

When abundant, as is the case in hundreds of Minnesota lakes, the common carp has devastating effects on aquatic plants, waterfowl and water quality so if carp movement could be controlled using inexpensive barriers, it would be enormously beneficial. The aims of this project were to design, construct, and test bubble curtains as barriers for carp. This work comprised three main results. In result 1 bubble curtain design was investigated. Focus was placed on generating, measuring, and controlling sound and flow fields produced by bubble curtains. This work led to designs that reliability produced sound in ranges that deter carp movement. Result 2 focused on the laboratory tests of these designs. This work, the first rigorous tests of bubble curtains, showed that these barriers can be >75% effective in reducing fish passage in laboratory tanks. In addition, a model capturing fish behavior in the vicinity of the barriers was built and shown to have predictive qualities. Result 3 tested bubble curtains in the field, in collaboration with Ramsey-Washington Metro Watershed District. A barrier was constructed in Kohlman Creek (Maplewood, MN) based on the optimized design in result 2. The barrier was positioned as a cross-stream barrier in a fast flowing stream at the request of the local biologist. It cost $20,000 ($15,000 for infrastructure, $5,000 for bubble curtain supplies) to build and then <$300 per month to operate. It has proven capable of stopping 57±12% of carp moving downstream, but only delayed upstream-moving fish by 6 hours. We concluded that while bubble curtains have potential to inexpensively stop young carp from leaving nursery habitats in which they are already established, they may not be an effective block in fast flowing tributaries. Nevertheless, their low cost and versatility appear to warrant their being tested (with enhancements) to deflect carps from entering locations such as large rivers or lakes where other technologies are ill-suited or unaffordable.

### Project Results Use and Dissemination

The engineering design and testing of the bubble barriers has been documented in the MS thesis by Dan Zielinski

- Zielinski, D.P. (2011) Bubble barrier technologies for common carp, University of Minnesota, MS Thesis

The laboratory and field testing, modeling and data analyses is reported in a the PhD Thesis of Dan Zielinski

- Zielinski, D.P. (2013) An engineering perspective on invasive fish control: A study of bubble curtain deterrent systems to control carp movement, University of Minnesota, Ph.D. Thesis.

This work also reports the behavioral modeling of fish in the vicinity of the barrier along with the development of the necessary theory to support this model.

A detailed reporting of the laboratory effectiveness is found in the paper

- Zielinski, D.P., Voller, V.R., Svendsen, J.C., Hondzo, M., Mensinger, A.F., Sorensen, P., (2013) Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp. Submitted to Ecological Engineering.

A detailed reporting of behavioral model is found in the paper

- Zielinski, D.P., Hondzo, M., Voller, V.R. (2013a) Mathematical evaluation of behavioral deterrent systems to disrupt fish movement. Submitted to Ecological Modeling.

Copies of these papers will be submitted once they are accepted for publication.

Elements of all of these works was presented at a number of conferences

- Zielinski, D.P., Sorensen, P. (2013), Field study of an air bubble curtain to inhibit Common Carp movement, *Minnesota Chapter of American Fisheries Society Annual Meeting,* St. Cloud, MN, USA.
- Zielinski, D.P., Voller, V.R., Svenden, J., Hondzo, M. Mensinger, A., Sorensen, P. (2012), Inhibiting Common Carp Movement with a Bubble Curtain, *142nd Annual Meeting of the American Fisheries Society*, St. Paul, MN, USA.
- Zielinski, D.P., Voller, V.R., Svenden, J., Hondzo, M. Mensinger, A., Sorensen, P. (2011), Controlling the Movement of Invasive Species, *2nd Annual Upper Midwest Stream Restoration Symposium*, Oconomowoc, WI, USA.
- Zielinski, D.P., Voller, V.R., Svenden, J., Hondzo, M. Mensinger, A., Sorensen, P. (2011), Bubble Barrier Technologies for Common Carp, *Minnesota Chapter of American Fisheries Society Annual Meeting*, Sandstone, MN, USA.

# Trust Fund 2009 Work Program Final Report

**Date of Report:** July 30, 2013
**Final Report**
**Date of Work Program Approval:** June 16, 2009
**Project Completion Date:** June 30, 2013

**I. PROJECT TITLE**: Controlling the Movement of Invasive Fish Species


| | |
|---|---|
| **Project Manager**: | Vaughan R. Voller |
| **Affiliation:** | U of M, Department of Civil Engineering, SAFL |
| **Mailing Address:** | Mississippi River at 3rd Ave S.E. |
| **City / State / Zip:** | Minneapolis, MN 55414 |
| **Telephone Number:** | 612-625-0764 |
| **E-mail Address:** | volle001@umn.edu |
| **Fax Number:** | 612-624-4398 |
| **Web Page address:** | http://personal.ce.umn.edu/~voller/ |


**Location:** Laboratory studies will be conducted at the Saint Anthony Falls Laboratory, Minneapolis and the St. Paul Campus of the University of Minnesota.

| | | | |
|---|---|---|---|
| **Total Trust Fund Project Budget:** | **Trust Fund Appropriation:** | **$** | **300,000** |
| | **Minus Amount Spent:** | **$** | **292,695** |
| | **Equal Balance:** | **$** | **7,305** |

**Legal Citation: M.L. 2009, Chp.143, Sec. 2, Subd. 6d.**

**Appropriation Language:**
$300,000 is from the trust fund to the Board of Regents of the University of Minnesota to develop and test sonic barriers that could be effective in preventing and controlling the movement of invasive carp in Minnesota's waterways. This appropriation is available until June 30, 2012, at which time the project must be completed and final products delivered, unless an earlier date is specified in the work program.

## II. FINAL PROJECT SUMMARY

When abundant, as is the case in hundreds of Minnesota lakes, the common carp has devastating effects on aquatic plants, waterfowl and water quality so if carp movement could be controlled using inexpensive barriers, it would be enormously beneficial. The aims of this project were to design, construct, and test bubble curtains as barriers for carp. This work comprised three main results. In result 1 bubble curtain design was investigated. Focus was placed on generating, measuring, and controlling sound and flow fields produced by bubble curtains. This work led to designs that reliability produces sound in ranges that deter carp movement. Result 2 focused on the laboratory tests of these designs. This work, the first rigorous tests of bubble curtains, showed that these barriers can be >75% effective in reducing fish passage in laboratory tanks. In addition, a model capturing fish behavior in the vicinity of the barriers was built and shown to have predictive qualities. Result 3 tested bubble curtains in the field, in collaboration with Ramsey-Washington Metro Watershed District. A barrier was constructed in Kohlman Creek (Maplewood, MN) based on the optimized design in result 2. The barrier was positioned as a cross-stream barrier in a fast flowing stream at the request of the local biologist. It cost $20,000 ($15,000 for infrastructure, $5,000 for bubble curtain supplies) to build and then <$300 per month to operate. It has proven capable of stopping 57±12% of carp moving downstream, but only delayed upstream-moving fish by 6 hours. We concluded that while bubble curtains have potential to inexpensively stop young carp from leaving nursery habitats in which they are already established, they may not be an effective block in fast flowing tributaries. Nevertheless, their low cost and versatility appear to warrant their being tested (with enhancements) to deflect carps from entering locations such as large rivers or lakes where other technologies are ill-suited or unaffordable.

**III. PROGRESS SUMMARY AS OF *(date)*:**

**Amendment Approved: 12/17/2009**
Quoting from the letter of Prof Cuthbert send to LCCMR on 11/04/2009. “Unexpectedly the deep well that supplies this center with water suffered a complete failure this past August. After a lengthy process we have discovered that premature pump failure was the cause and that we need to replace the pump along with many of its associated wires and pipes to get the center running so that the studies can take place. The total cost of the repair is estimated at $20,000. We have secured $5,000 from the College and I am contributing $5,000 from the department for this replacement cost. The only capitalized cost will be the $7,000 pump, which will come from university funding. Both of the LCCMR projects which are slated to use this facility have budgeted for supplies for this center and the PIs are willing to support this repair effort ($5,000 Pelican; $4,000 Voller)”

The functioning of the deep well in the aqua center referred to in Prof Cuthbert’s letter is critical element in the completion of the work in Result 2. In addition a more detailed testing is now planned for Result 2, requiring a reassignment of effort.

To cover the contribution to the deep well fix identified in Prof Cuthbert’s letter and the increased effort in Result 2, I am requesting a shift of $6,109 into the Result 2 Budget. This will cover the $4,000 of the well fix cost plus a $2,109 increase in personnel costs. This additional funding is covered by a reduction of $1,308 in the personnel costs of Result 1, a reduction of $4,210 in the personnel costs of Result 3, and a reduction of $268 in the non-capital equipment cost of Result 3.

**Summary 3/31/2010**

A preliminary design of bubble curtain fish barriers has been completed (see detailed report in **Result 1**). Two distinct barrier designs have been identified, developed and build. One is based on a fine-bubble diffuser and the other on a coarse-bubble diffuser. The primary physical properties that can be controlled through diffuser design are the bubble size, frequency of formation, and density of bubble curtain. Preliminary results indicate that these two designs will be able to produce a wide range of barrier induced physical, flow and sound conditions. The next stage of the project is to measure and quantify the physical fields generated by the designed barriers,

As the project moves forward the plan is to incorporate the barrier deigns into experiments that will determine the response of fish in the vicinity of a bubble diffuser barrier operating under a variety of conditions. In addition to well designed and understood bubble diffuser technologies this requires experimental set ups for testing fish behavior. Of key importance is a controlled environmental that can track fish movements automatically through the use of PIT tags. At this point such an experimental facility has been realized and the effective ways of tracking fish with PIT tags has undergone preliminary testing.

**Amendment Approved 6/25/10**

We are requesting that a small amount of funds ($3,576) initially allocated for civil service staff at SAFL be re budgeted for an undergraduate student worker. Note this will require adjustment in personnel costs and a reduction of the SAFL lab fee, see Budget Justification.

**Summary 9/30/2010**

A key result this last half year has been the development of a bubble barrier that shows a reasonable level of effectiveness. Over a 7 hour testing period it has been demonstrated that the barrier can reduce fish passages by 75%. This level of effectiveness could be sufficient for the use of these barriers in the management of common carp movements. Ongoing work is directed at (i) further improving the barrier design and (ii) developing an understanding of fish behaviors in the vicinity of the barriers. Below a more complete summary is provided. Full details are given further below in reporting the finding of the Project Results.

A study to identify and quantify the hydrodynamic fields generated by a bubble curtain barrier has been completed (see detailed report in **Result 1**). The focus of the measurements has been on the flow and acoustic fields generated by the two diffuser types. Understanding the physical fields will help direct the design of barriers to be tested with carp at the Aquaculture Center. Measurements have revealed that the fine-bubble diffuser generates a relatively strong flow field, but weak acoustic field; while the coarse-bubble diffuser generates a weaker flow field, but considerably stronger acoustic field. Both diffusers were found to generate a sound that is within the hearing range of carp that is significantly higher than background noise in the flumes.

A PIT tag system to detect carp movement within the test tank at the Aquaculture Center was developed and tested (see detailed report in **Result 2**). The PIT tag system includes three to four antennas spanning the channel width at evenly spaced locations around the test channel. The antennas passively detect when a carp implanted with a PIT tag (microchip) passes through a specific point in the tank. The system has been tested to be approximately 99% accurate to detect carp passage. Along with the tracking system, a strict testing protocol has been developed to restrict the amount of variables influence carp behavior between tests.

The initial Mark I barrier test included a single fine-bubble diffuser with an air-flowrate of 1 and 2.5 $Ls^{-1}m^{-1}$. The lower flowrate test had a dual objective of proofing the PIT tag tracking technology and initial assessment of viability of bubble barriers. The Mark I barrier was found to delay carp movement by approximately 15 seconds, **but did not prevent passage of carp over the bubble barrier.**

Initial barrier tests and physical measurements indicating that larger hole diameters generates a stronger acoustic field led to the development of the more vigorous Mark II barrier. The Mark II barrier consists of 6 diffusers ranging from a fine-bubble diffuser on the up-stream end to an ultra-coarse-bubble diffuser on the down-stream end, while four coarse-bubble diffusers occupy the space between. The purpose of the bubble size increase was to generate a sharp sound pressure level gradient across the entire thickness of the barrier**. The Mark II barrier was found to reduce carp passage by 75%; a number that falls within a range where the management of carp movement with bubble technologies may be possible.** Full details and statistical analysis of the Mark I and II barrier tests are provided in **Result 2**.

As the project continues, the plan is to perform more robust testing of the Mark II barrier to confirm the positive results, and develop a Mark III barrier to improve carp deterrence. Further development will work to include an underwater transducer to create a precisely controlled acoustic barrier. The barrier designs will continue to be incorporated into experiments that will determine the response of carp within close proximity of the barrier. An optimal barrier design will eventually be implemented in a real field setting either at the SAFL Outdoor Stream Lab or a select field site.

**Amendment Request 3/31/11**

Due to personnel changes we will no longer be using our post-doc position. We intent that the components of the work plan assigned to this position to be taken over by graduate students. To allow for this we would like to shift the remaining budget assigned for the post-doc into the budget line for graduate students (see amended Attachment A).

In relation to the above we note that our current specified end date is 12/30/2011. We understand, however, that per the appropriation language, the money is technically available until June 30, 2012. As such, to allow for completion of the work we would like to also amend the project end date to June 30, 2012.

In addition, as the project has unfolded we have realized that the experimental and testing protocols developed in Results 1 and 2 will continue to be revised and used as we move into field scale testing. As such, we would also like to adjust the end dates of Results 1, 2, and 3 to coincide with the project end date.

**Summary 3/31/2011**

A study to identify how environmental effects modify the physical fields generated by a bubble barrier is nearing completion (see detailed report in **Result 1**). The focus of the measurements has been to determine how depth and flow variations change the flow and sound fields reported in **Result 1**. Understanding how the environmental effects modify the fields will provide some insight into acceptable flow and depth ranges that the barrier can be expected to perform without a drop in efficiency. Measurements have revealed that increased depth decreases the flow strength, but decreased depth increases the sound gradient. Flow normal to the bubble curtain was found to deform the curtain in the direction of flow; this deformation was evident in the sound and flow fields for both diffuser types. The barrier is not expected to have any significant decrease in the sound field for flows less than 30cm/s.
Further development and testing of the barrier design has been undertaken. Similar to the development of the Mark II barrier, the Mark III barrier was developed to maximize the sound production of the barrier by bubble formation. The Mark III barrier consisted grid configuration of all ultra-coarse-bubble diffusers, supplied with a three-fold increase in air over the Mark II barrier. Full details and statistical analysis of the Mark III barrier tests are provided in **Result 2**. **The Mark III barrier was found to reduce carp passage by 75%; similar to the results of the Mark II barrier.** The lack of increased effectiveness may indicate that we have reached the maximum stopping potential of bubble sound-driven barriers. Further investigation in the biological flume at the Aquaculture Center and the physical flume at SAFL will look at using sound generation from underwater transducers. Although the bubble barrier alone could be a useful component in an integrated management strategy for controlling movement and recruitment of carp it would not be 100% effective at stopping juvenile carp movement in a given reach.

A macro-behavior study of the carp was also completed, with a purpose of understanding the behavior of carp in the vicinity of the bubble barrier. By studying the dispersal of carp during the behavioral tests, the carp clearly correlated their movements to the presence of the small current present in the biological flume in the absence of the barrier. With the barrier operating, this behavior became clearly compromised and no distinct directional motion was observed. Full description of this study is provided in **Result 2**.

**Summary 9/30/2011**

Following the successful completion of the initial development (Result 1) and testing (Result 2) the latest period of work has consisted in translating these developments into a field setting and preparing for further barrier testing and development. In the former a field version of the bubble barrier has been constructed and successfully deployed in a field setting –the OSL at SAFL (see **Result 3**). Work in the next period will involve a testing of the effectiveness of this barrier using a modified version of the testing protocol developed previously in this project. Beyond this, plans are in place to implement a barrier in Markham Pond, more details are provided in **Result 3**. At the same time that we have been investigating the field implementation of the barrier we have also been working on improving our current barrier design by adding additional sound generation via speakers. An outline of this design improvement is provided under **Result 1**, and an outline of upcoming effectiveness tests are described under **Results 2**.

In addition to the item described above, articles featuring the bubble barrier research have been written on the University of Minnesota website ("Cacophony may curb carp" August 2011) and Minnesota Public Radio website ("Sonic bubble barrier is latest hope to control carp invasion" August 2011). A journal manuscript addressing the laboratory results of the Mark I through Mark III barrier trials will also be submitted to the Journal of Fisheries Management and Ecology by the end of October.

**Amendment Request 12/16/2011**

Up to this point our bubble barrier development has been very successful. By the current projected end date (June 30, 2012) we fully expect to have met our main research objective of developing the technology with relevant and laboratory and initial field (OSL) testing. Our work has stimulated a wide interest among watershed managers to the point where the Ramsey Watershed is proposing to partner with us in designing and undertaking a more significant practical field test of our barrier technology in Kholman Creek near Maplewood. This would represent a significant value added to our field trials outlined in Result 3 of the work plan. Completion of such a test, however, will require additional time. As such, we would like to request an extension on the end date of the work plan until June 30, 2013. This extension will require a re-allocation of funds assigned within the Result 3 Budget. Since this will involve less testing at the SAFL OSL site there will be a reduction in budget items associated with the lab personnel and "lab-fees" line items. At the same time this new field effort will require additional graduate and under graduate student resources. As such all salary savings will be reallocated to cover additional undergraduate and graduate student salaries. This new filed effort will also require some reallocation of Supplies and Equipment funds from Result 1 to Result 2 and Travel Funds from Result 2 to Result 3. In the first place, the remaining funds in the non-capital equipment budget line ($3798) and supplies line ($3245) will be moved into the matching line items in Result 3. These additional funds will be used to cover some fabrication and electrical installation costs for the field barriers, the purchase of a filed based PID tag system for the field fish. In addition to re-allocating supplies and equipment funds the $500 travel fund in Result 1 and $1500 of the travel funds in Result 2 will be added to the travel fund in Result 3. This is to cover truck rental and other transportation costs related to deploying large equipment into the field. These budget changes are reflected in the amended budget Attachment A

**Summary 3/15/2012**

In the last period the main lines of work (expanded below in the results section) have been

Results from two behavioral trials in the Outside Stream Lab (OSL) at SAFL were collected. These trails, although preliminary in nature, indicated a reduction of 55% in fish passages. See summary in **Result 3**.

Behavioral trials utilizing an underwater speaker-only trial, consistent with physical measurements provided in **Result 1**, were initiated at the Aquaculture Center. See summary in **Result 2**.

The proposal for building and testing a full scale prototype bubble curtain barrier in the Lake Phalen chain of lakes was accepted by the Ramsey-Washington Metro Watershed District. Details of the design and implementation are provided in **Result 1** and **Result 3**.

In addition to the item described above, the following coverage on bubble curtain barrier research has been generated: "Legislators, researchers fighting silver Asian carp in Mpls." (Kare 11); "Upper St. Anthony Lock Touted As Carp Blocker" (St. Paul Pioneer Press); "Upper St. Anthony lock touted as Asian carp blocker" (MPR); "Sen. Klobuchar and other legislators talk fish" (Minneapolis Star Tribune); "Bubble Barrier May Protect MN Waters From Asian Carp" (WCCO 4); "Leaders Highlight Efforts to Fight Spread of Asian Carp" (KSTP 5). Further development of a manuscript for submittal to the Journal of Fisheries Management and Ecology, or equivalent peer reviewed journal, is ongoing.

**Summary 9/30/2012**

In the last period, the main lines of work (expanded below in the results section) have been

The full scale prototype bubble curtain barrier was constructed and installed in Kohlman Creek, immediately upstream of Lake Kohlman in Maplewood, MN. Photographs of the site and description of the monitoring system and preliminary results are provided in **Result 3**.

The acoustic field generated by the Mark III barrier, speaker-only barrier, and speaker-bubble barrier was mapped in the laboratory tank to ensure similar characteristics were observed during the flume experiments. Mapping results are provided in **Result 1** and **Result 2**. Results of the corresponding behavioral trials of the revised speaker barrier and speaker-bubble barrier are provided in **Result 2**.

The results of the laboratory trials and preliminary results of the Kohlman Creek barrier were presented in "Inhibiting common carp movement with a bubble curtain" at the American Fisheries Society meeting at St. Paul, MN in August 2012. Work completed in this period is currently being integrated into the manuscript covering the laboratory findings for a peer-reviewed journal.

**Summary 3/30/2013**

In the last period, the main lines of work (expanded below in the results section) have been

Additional field trials were performed on the prototype bubble curtain barrier in Kohlman Creek. Details on the preliminary results are provided in **Result 3**.

In an attempt to better understand the impact of acoustic cues on fish avoidance of a bubble curtain barrier, additional sound measurements and laboratory trials were performed using the speaker/bubble curtain system with randomized pure tone signals (chosen from the most sensitive region of the carp hearing thresholds). Preliminary results of sound measurements and behavioral trials are provided in **Result 2.**

The preliminary results of the Kohlman Creek barrier project were presented in "Field study of an air-bubble curtain to inhibit common carp movement" at the Minnesota Chapter of the American Fisheries Society meeting at St. Cloud, MN in March 2013.

These results reported on in this summary are under analysis and will be fully reported in our final report.

**Amendment Request 5/20/2013:**

We are requesting an amendment to transfer approximately $4200 from the Result 2 budget to the Result 3 budget and to transfer approximately $7500 from the supplies and $1200 from the travel budget category into the equipment category for Result 3. This will allow for travel and supplies balances and the purchase of the following equipment (also listed in section V of work plan) needed for continuation of the project:

-Hydrophone and recorder plus cables, batteries, memory cards (to measure and create sound, B&K 8103 or similar, $1000 per). Whole system approximately $3,600
-PIT Tag system, antenna wire, antenna packs to detect fish at field barrier site~$2,700
-PIT reader, tags ~$3,300
-Computer for data collection and signal processing from hydrophones ~$1,200
-2 regenerative blowers ($762/ea) ~$1,600
-Underwater IR camera + DVR monitor ~$900
-2 speakers Lubell Labs ($900/ea) ~$1,800
-Radio tags ~$3,300

This equipment will continue to be used to develop and test barriers and deterrents for preventing and controlling the movement of invasive carp in Minnesota's waterways under a 2012 ENRTF appropriation to the University of Minnesota's Minnesota Aquatic Invasive Species Research Center.

**Amendment Approved: 5/31/2013**

**Amendment Request 7/18/2013**

Due to changes in University fringe rate we are requesting that our total budget for salary be increased by $1,563, from $261,000 to $262,563. Due to unexpected lower costs this small amount of additional funding is available in the non-capital equipment budget line of Result 3. In this way we are requesting that the non-capital equipment budget of results 3 be reduced from, $19,840 to $18,277 and the total non-capital equipment budget for the project be reduced from $28,402 to $26,479.

**Amendment Approved: 7/19/2013**

**Summary: 7/30/13**

In the last period, the main line of work has been on additional field trials using the prototype bubble curtain barrier in Kohlman Creek. Details on the preliminary results are provided in **Result 3**.

## IV. OUTLINE OF PROJECT RESULTS*:*

**Result 1:** Laboratory Investigation: Engineering

**Description:** The objective of this phase of the study is to develop the necessary engineering infrastructure to allow for the building, design and optimization of bubble curtain barriers. The main goals are to (i) design and develop devices for creating bubble curtains in flume systems, (ii) to identify, measure the physical fields created by said bubble curtains, and (iii) to understand how these physical fields are modified by different operating (pressure, orifice placement, etc) and environmental (flow velocity, flow depth, temperature, etc) conditions.

**Summary Budget Information for Result 1:** **Trust Fund Budget:** **$ 90,838**
**Amount Spent:** **$ 90,838**
**Balance:** **$ 0.00**

| **Deliverable** | **Completion Date** | **Budget** |
|---|---|---|
| **1.** Designs of diffusers for bubble curtains | 3/31/2010 | $33,000 |
| **2.** Quantitative description of the physical fields generated by sub-aqueous bubble curtains | 9/30/2010 | $33,000 |
| **3.** Quantitative description of the effects of design and environmental parameters on the physical fields generated by a bubble curtains | 6/30/2012 | $24,838 |

**Completion Date:** 6/30/2012

**Final Report Summary**

### 1.0 Introduction

Common carp (*Cyprinus carpio*) comprises over half the biomass in a third of Minnesota lakes. The feeding habits of this species significantly disrupt lake sediments leading to an over-enrichment of nutrients which dramatically reduces water quality. Great ecological benefit will be gained if effective barriers can be constructed to control the movement of invasive carp. A class of barrier technology, that shows promise for this application, is based around the use of air bubble curtains that generate acoustic and other hydrodynamic fields. The goal of the current project is to design and assess the effectiveness of bubble curtain barrier technologies as a means of controlling carp movements in the connection channels of lake systems.

The use of acoustic and hydrodynamic barriers for the control of invasive species remains largely untested (Webb et al. 2008). Only a few publications regarding the use of bubble curtains as a barrier are in peer-reviewed literature; these studies focused on a range of species including Bighead Carp (Taylor et al. 2005), Atlantic Salmon (Welton et al. 2002), and Eurasian Ruffe (Dawson et al. 2006). The Taylor and Welton studies used a bubble curtain in conjunction with an independent sound projector. The Dawson study paired the bubble curtain with an electrical barrier. The bubble diffusers were created by holes drilled into PVC pipe with air-flow rates ranging from approximately 0.1 to 1.0 $Ls^{-1}m^{-1}$. The bubble diffuser utilized by Taylor and Welton was a proprietary device developed by Fish Guidance Systems. The diffuser utilized by Dawson consisted of 0.4 to 1.0 mm holes drilled at evenly spaced distances of either 6.25 or 12.5 mm. These studies did not focus on using the bubble curtain as a primary means to deter the fish, nor was there an in-depth analysis of the physical fields generated.

Outside of the aquaculture field, bubble curtains or diffusers have been studied by engineers and scientists as a means to aerate and induce mixing in stratified lakes. These studies investigated the generated velocity fields (Brevik et al., 2002) and turbulence (Chen et al., 2001); however, the depths considered for these studies were considerably greater than 1m for most cases. The implementation of a bubble curtain for this project will be in a connecting stream between ‘nursery’ lakes, with depths typically less than 0.5 m. In addition, any research studying acoustic properties of bubble curtains have been limited to use as an acoustic screen for underwater noise. The bubble curtains used in the Brevik study were coarse bubble diffusers made by drilling 0.8 to 0.5 mm holes into a steel pipe and plexiglass tube with an air-flowrate of ranging from approximately 1 to 4.5 $Ls^{-1}m^{-1}$.

The objective of this phase of the study is to develop the necessary engineering infrastructure to allow for the building, design and optimization of bubble curtain barriers. Based on the previously mentioned literature, the bubble diffusers will consists of plastic tubes with holes evenly spaced throughout. The primary physical properties that can be controlled through diffuser design is the bubble size, frequency of formation, and density of bubble curtain. This work is split into two phases: 1) quantify sound and fluid flow characteristics produced by bubble curtains; then 2) use this information to develop bubble curtain barriers to inhibit common carp movement.

### 1,1 Fish Sensory Systems

Carp, as all fish, utilize their lateral line system to detect fluid motion in their environment through the use of microscopic sensory units called neuromasts (Urick, 1975); therefore, the flow field generated by rising bubbles should be quantified as it is surely detected by nearby carp. The flow field can be decomposed into two categories: domain scale velocity field characterized by recirculation cells (Brevik et al., 2002; Fannelop et al., 1991), and small scale turbulence (Chen et al., 2001; Kundu, 1990). Fish neuromasts range in size from 10 to 400μm in length and can detect minute fluid motions, presumably small eddies, along with the mean fluid flow (Urick, 1975). Eddies are identifiable structures that occur in turbulent flow which are typically defined by a spinning motion (Kundu, 1990), and start at a length approximately equal to the domain size (or flume width/depth/length) and through viscous forces are dissipated to less than 1mm in size. Characterizing the fluid motion and how diffuser type effects the magnitude of large and small scale fluid motion will help determine which scale of fluid motion influences carp movement more or at all.

Carp are identified as hearing specialists (Webb et. al., 2008), and their specific sensitivity to sound has been at the center of a wide variety of barrier designs (Popper and Carlson, 1998; Taylor et al., 2009; Webb et al., 2008; Welton et al., 2002). The main goal of an acoustic barrier is to generate a sound that is powerful enough to incite an avoidance response while not allowing the fish to acclimate to a monotone sound (i.e. single frequency and amplitude). A bubble barrier is expected to generate sound through the creation of bubbles (Lin et al., 1994) and fluid motion driven by rising bubbles (Tonolla et al., 2009). The key components to a sound field detected by carp are the frequency and amplitude of a sound pressure wave; the sound must be within the carp hearing frequency range and powerful enough to be heard over background noise (Popper, 1972). Sound pressure levels generated by a single bubble have been documented (Leighton, 1994); however, a robust description of the SPL generated by a bubble barrier is not available in literature.

## 2.0 Methods

Testing of the bubble diffusers will be performed at the University of Minnesota's Saint Anthony Falls Laboratory (SAFL) and the Aquaculture Center. Initial testing without fish, to determine the generated acoustic and hydrodynamic fields will be performed at SAFL; while testing for efficacy with live specimen will be performed at the Aquaculture Center. The SAFL flume is a straight flume, fed by the water diverted from the Mississippi River, with the following dimensions: 20 in. wide x 36 in. high x 30 ft long. The bubble diffusers will be placed at the mid-point of the flume anchored with a wood base buried in sand. Air will be supplied to the bubble diffusers through a laboratory compressed air line capable of high pressure and high volume. Physical fields will be measured by various instruments attached to a fully articulated cart located along the length of the flume.

The Aquaculture Center flume is a circular flume constructed from setting a 1 m diameter tank inside a 3 m diameter tank. Air will be supplied through the use of a portable air-compressor. Select measurements of the physical fields can be obtained through the use of a semi-mobile instrument bracket. Air-supply at both sites will be monitored and controlled through the use of a pressure gauge and rotameter.

A variety of instruments were used to characterize the physical fields generated by the bubble curtains. The following is a list of apparatus used and specific fields measured:

1. SonTek 16-MHz MicroADV (Acoustic Doppler Velocimeter) – three-dimensional velocity measurements at a sample rate of 50-Hz

2. MSCTI SN 5 (20 K Temperature Probe) – instantaneous temperature at a sampling rate of 100-Hz

3. Dissolved Oxygen Probe – dissolved oxygen level sampled at a rate of 100-Hz

4. BK 8103 Hydrophone – piezoelectric transducer to measure sound pressure level at 50-kHz

Each of these instruments were attached to a mobile cart and mounted on a telescoping arm to repeatedly take simultaneous measurements upstream and downstream of the barriers. Velocity measurements from the ADV were collected and analyzed using the SonTek software package HorizonADV and WinADV. The temperature and dissolved oxygen probe data were collected using a data acquisition board and software program TracerDAQ. A one minute continuous sample was taken at each measurement location of the velocity, temperature, and dissolved oxygen level. Hydrophone data collection required the use of a 5V power pre-amplifier and National Instruments SC-2345 signal conditioning and connector box to digitize the signal. The data was finally collected by the National Instruments software package LabView and further analyzed using Matlab. At each measurement location, four 10-sec sound wave samples were obtained.

## 3.0 Bubble Curtain Background

Understanding the formation of a single bubble through an orifice is vital to developing diffusers that can create well defined and predictable physical fields. Bubble formation is driven by two main components, buoyancy and surface tension. The buoyancy force acts to drive the bubble towards the surface, while the surface tension acts to keep the bubble attached around the orifice. As the bubble size increases, the buoyancy force overcomes the surface tension and the bubble detaches from the surface. Bubble formation creates pressure waves (sound) throughout the liquid and accounts for most of the sound generated by a bubble curtain. As the bubbles rise, they coalesce (two or more bubbles form one larger bubble). The thickness of the bubble curtain also increases as the bubbles rise. These characteristics were utilized in the design of the two diffuser types: fine-bubble and coarse-bubble.

Understanding what fields are generated by the diffuser will help create a clear link to what physiologic responses may cause carp to be deterred by said barrier. The measurements taken on flume experiments at SAFL have focused on two main physical fields: flow and sound pressure level (SPL). Temperature and dissolved oxygen levels were also measured to gain additional understanding of fluid interaction with the bubble plume; however, at this time no distinct features were evident in these fields to possibly deter carp. Each diffuser type (coarse-bubble and fine-bubble) was tested individually at two increasing air flow-rates to determine the distinct differences between types, and how the physical fields are manipulated. Measurements were taken along the centerline of the flume in a grid pattern extending up to 4m up- and down-stream of the barrier over the full depth of flow. Note that all experiments were performed without any channel flow. Figure 1 displays the diffuser set-up and measurement locations.

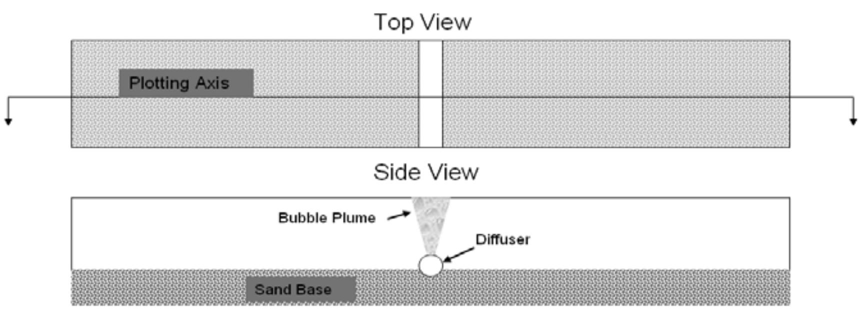



Figure 1. Diffuser set-up and measurement location

We characterized the sound generated by the bubble barrier and determined whether it is substantial enough to be detected by carp.

### 3.1 Coarse-Bubble Diffuser

The first of two diffuser types is identified by the relative large size of bubbles produced when air is forced through the diffuser. The coarse-bubble diffusers consist of PVC pipe with holes manually drilled at constant spacing. The hole sizes range between 1 mm to 10 mm, and the spacing varies between 0.5 cm to 10 cm. The minimum hole size is determined by the smallest available drill bit and large diameter holes (>10 mm) will not be considered as maintaining a constant air-flow through every hole would be suspect. Figure 2 displays the typical bubble curtain generated by the coarse-bubble diffuser. Note the mixture of large and small bubbles.

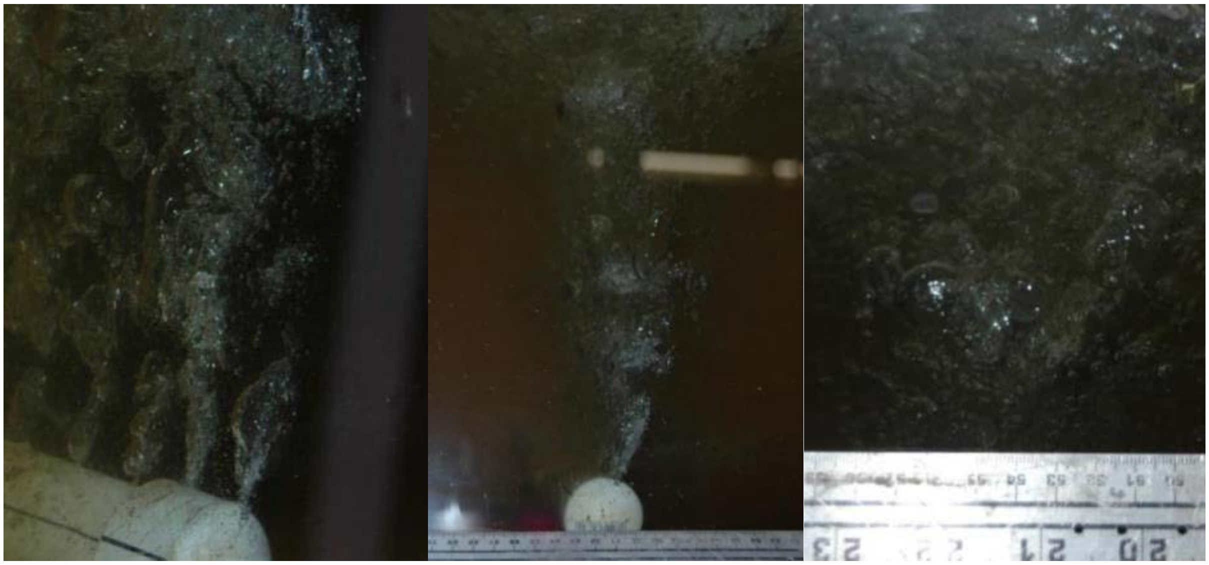


Figure 2. Typical bubble curtain provided by coarse-bubble diffuser (1mm holes at 2.5 cm spacing)

Work by Lin et al. (1994) indicated that the diameter of a detached bubble from an orifice will always be larger than the orifice; they also stated that for small orifices, the bubble size in highly dependent on the liquid and diffuser surface tension. The result of this research indicates that 2.5 mm and 1 mm diameter orifices, drilled in the same material, would create similar sized bubbles. The typical bubble size generated by the 1 mm hole diffusers near the PVC and surface are approximately 10 mm and 15 mm, respectively.

The lateral spacing of the holes in the PVC provides control over the density of the bubble curtain. Spacing too large would create gaps near the diffuser, possibly large enough for fish passage. Spacing too small creates immediate overlapping of individual bubble plumes; however, spacing of less than 0.5 cm is time consuming and difficult to maintain a perfectly straight line of holes. Only one line of holes restricts the thickness of the bubble curtain; however, multiple diffusers can be used in series to create a thicker curtain.

The final physical feature that can be controlled to manipulate the bubble curtain is the air-flow rate. The PVC pipe used for this application is not rated for high pressures, which limits the maximum air-flow rate that can be used. Lin et al. (1994) found that increasing the air-flow rate does not increase bubble size, but increases the frequency at which bubbles are created. As an initial condition for testing, the diffusers will be supplied with a low and high air-flow rate of 2.5 and 2.8 $Ls^{-1}m^{-1}$, respectively (flow rates are associated with air pressures of 50kPa and 100kPa, respectively). By inspection, an air-flow rate less than 2.5 $Ls^{-1}m^{-1}$ creates a thin, insubstantial bubble curtain.

### 3.2 Fine-Bubble Diffuser

The second type of diffuser to be considered for this research is a fine-bubble diffuser, which creates bubbles significantly smaller than the coarse-bubble diffuser. The fine-bubble diffuser consists of porous polyethylene, which is manufactured to have a complex, homogenous pore structure throughout the entire wall. A sample portion of I inch diameter porous pipe with a typical pore size of 35 microns was provided by GenPore Inc. The pore size can be reduced to 10 microns, but with reduced pore size, the chance of clogging increases. The porous pipe is also available in hydrophilic and hydrophobic formulations. The hydrophobic formulation will be utilized in this research based on the work by Lin et al. (1994). Figure 3 displays the typical bubble curtain generated by the fine-bubble diffuser. Note the almost homogenous, dense bubble curtain.

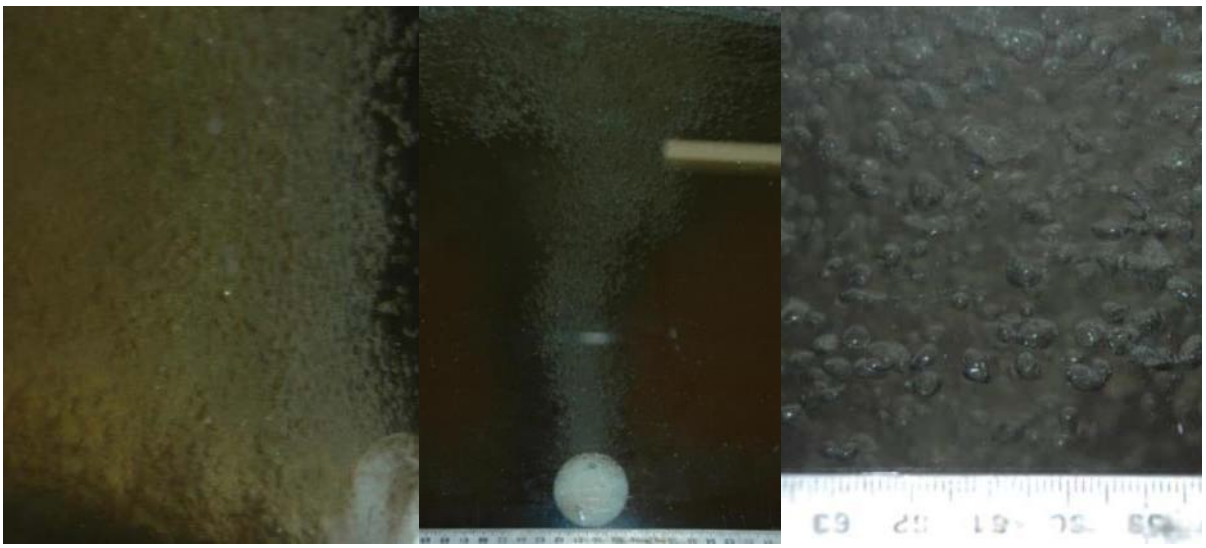


Figure 3. Typical bubble curtain provided by fine-bubble diffuser (30 micron holes)

The typical bubble size is 1-2 mm near the pipe, which is an order of magnitude smaller than the coarse-bubble diffuser formed bubbles. The bubbles near the surface are approximately 2-5 mm in size.

The thickness of the bubble curtain expressed by the porous pipe is slightly thinner than the pipe diameter, as bubbles are formed along the entire surface of the pipe; therefore, the curtain thickness is significantly larger than the coarse-bubble diffuser. The thickness of the curtain at formation causes the width near the water to be thicker than that generated by the coarse-bubble diffuser as well. The homogenous distribution of pores removes the chance for gaps to form laterally along the diffuser. In general, the bubble curtain created by the fine-bubble diffuser is far denser than that formed by the coarse-bubble curtain for a constant air-flowrate. As the air is expressed evenly along the surface of the fine-bubble diffuser, the curtain can lacks directional control. The fine-bubble diffusers will be subjected to the same air-flowrates as the coarse-bubble diffusers.

## 3.3 Hydrodynamic Fields Created by Bubble Curtain

Research by Brevik et al. (2002) and Fannelop et al. (1991) have shown that the domain scale velocity field generated by a bubble curtain can be broken down into two subcategories: near- and far-field. The far-field flow is dominated by a horizontal recirculation cell extending approximately two times the depth away from the curtain. The near-field flow is dominated by the vertical velocity of the bubble plume and occurs within close proximity of the bubbles. The distinct difference between these two categories is the maximum velocity in the far-field acts parallel to the channel flow while the near-field acts perpendicular to the channel flow, creating a sharp velocity gradient. As a carp presumably swims from far- to near-fields, the velocity gradient should be detected and may disrupt an up- or down-stream migration.

Using the MicroADV, we calculated the time-averaged velocity vector at various locations along the centerline of the SAFL flume up- and down-stream of the diffuser. From the velocity vectors we calculated the streamlines (the line tangent to the local velocity vector) for each given diffuser set-up. Figure 4 provides the velocity vector plot for the fine-bubble diffuser at an air flow rate of 2.5 $Ls^{-1}m^{-1}$ and set at a depth of 0.25 m. Figure 5 provides the corresponding streamline plot to the velocity vectors plotted in Figure 4. The streamline plot is included to highlight the location of the stagnation point, or center of rotation of the recirculation cell. Note, the x- and y-axis have been normalized by the depth of flow.

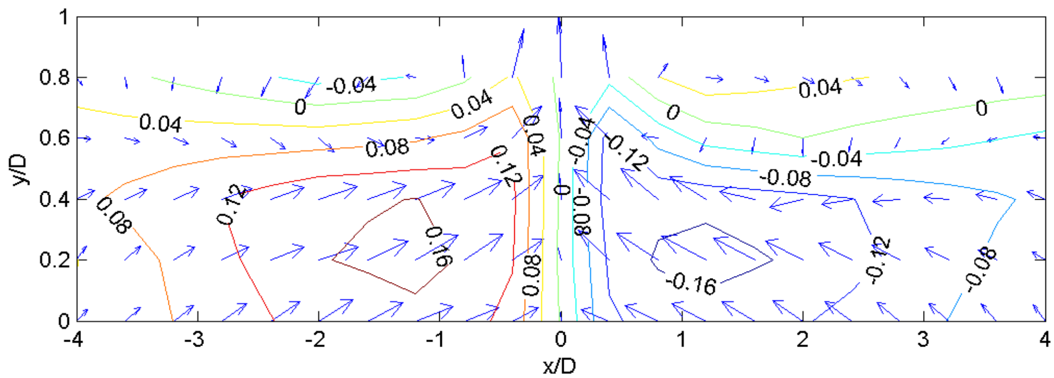



Figure 4. Velocity field for fine-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm (velocity contours are in m/s)

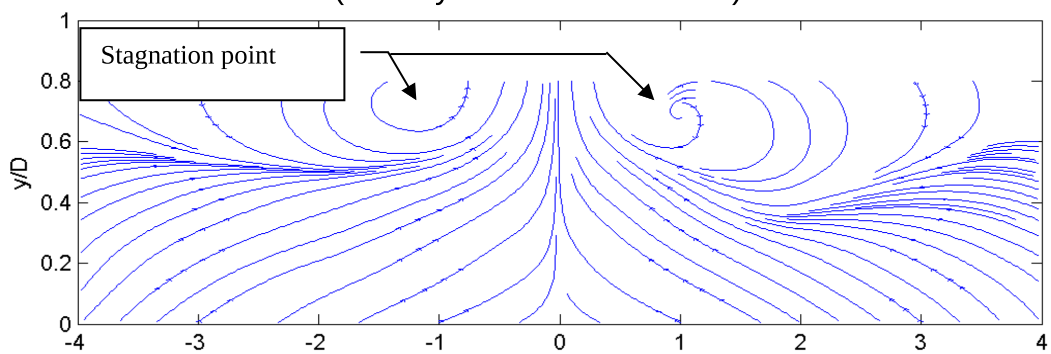



Figure 5. Streamline plot of velocity field generated by fine-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm

Figure 6 provides the velocity vector plot for the coarse-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and set at a depth of 0.25 m. Figure 7 provides the corresponding streamline plot to the velocity vectors plotted in Figure 6.

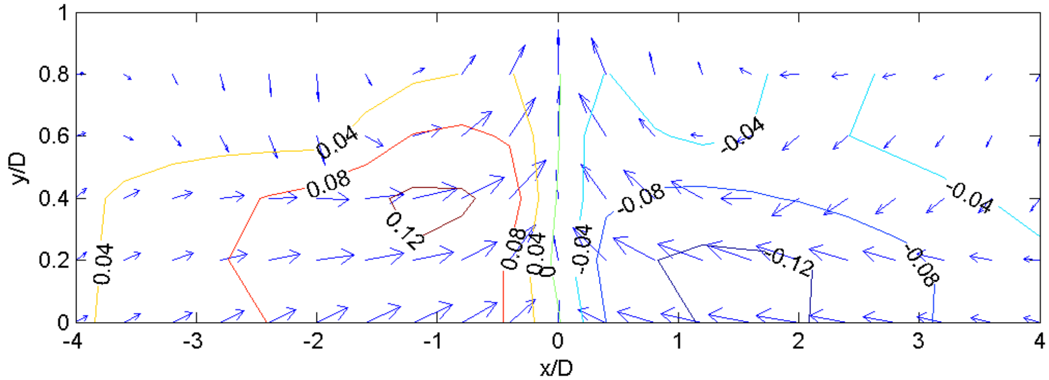



Figure 6. Velocity field for coarse-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm

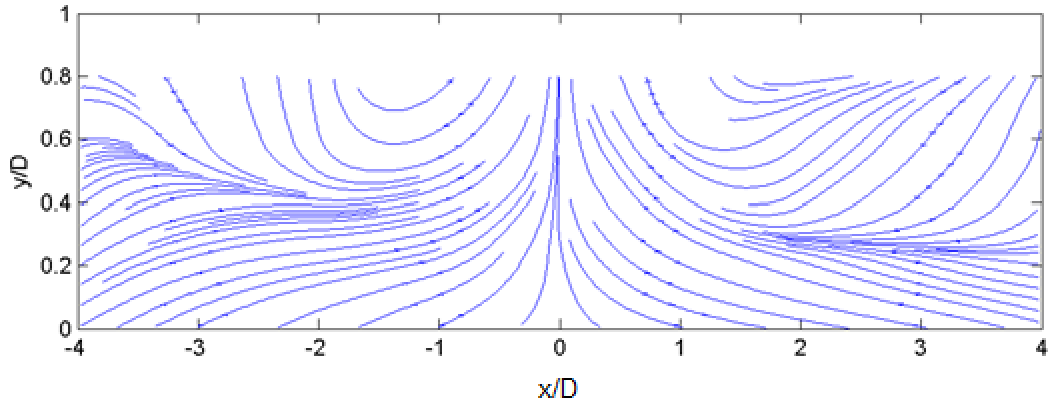



Figure 7. Streamline plot of coarse-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm

Comparison of the two different types of diffusers in Figures 4-7 indicate that the flow generated by the fine-bubble diffuser is stronger than the coarse-bubble diffuser (16 cm/s vs. 12 cm/s). The stagnation point for both configurations is located approximately at a similar horizontal position (x/D = +/-1). The vertical location of the coarse-bubble diffuser is unknown as it is located shallower than the ADV could measure, while the vertical position is approximately y/D=0.75 for the fine-bubble diffuser. The horizontal component of the velocity in the far-field, in the absence of mean channel flow, can be predicted by equations derived from the Entrainment Method (Fannelop et al., 1991) and Kinetic Energy Method (Brevik et al., 2002) using the air flow rate and depth of diffuser as dependent variables. The vertical velocity component is more difficult to predict using these models, but is of less significance in the far-field; therefore it was omitted. Both methods were used to compare with the velocity measurements; while each method predicted a similar maximum velocity, the Entrainment Method better predicted the stagnation line (points at which the horizontal velocity is zero). These predictive models will be used to specify what flow-rate may be required to create a recirculation cell with velocities that can overcome the mean channel flow (i.e. so the mean channel flow does not sweep the recirculation cell downstream).

Fluid motion detected by the lateral line system is not limited to large scale motion of water, as demonstrated by the recirculation cells in Figure 2-5, but includes the small scale water motions that are closer to the scale of the sensory unit itself. First, we must determine if the fluid motion, or eddy, itself is large enough to be detected by a neuromast, yet small enough as to not be interpreted as the mean flow. The smallest scale that an eddy can exist before viscous forces convert the mechanical energy into thermal energy is called the Kolmogorov length scale (Kundu, 1990); The Kolmogorov length scale was calculated at various points along the centerline of the flume by performing a fourier transform and cross correlation of the instantaneous velocity data obtained by the MircoADV consistent with (Kundu, 1990). Figure 8 and 9 provide a plot of the Kolmogorov length scale for the fine- and coarse-bubble diffusers in a 25 cm deep flow at an air flow rate of 2.5 $Ls^{-1}m^{-1}$.

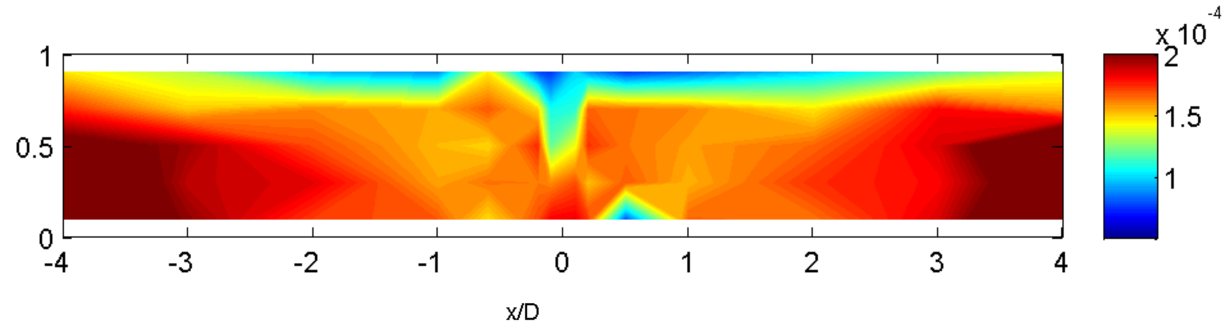



Figure 8. Kolmogorov scale for fine-bubble diffuser in depth D=25 cm (scale is in m)

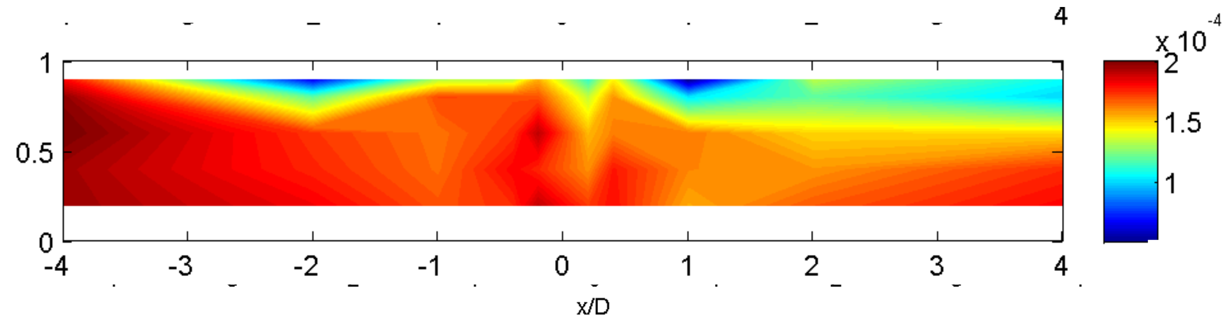



Figure 9. Kolmogorov scale for coarse-bubble diffuser in depth D=25 cm (scale is in m)

Note the eddies are sustained at much smaller scales close to the bubbles and surface, and that there is no significant difference between the fine- and coarse-bubble diffusers. The Kolmogorov length scale of each diffuser is approximately 0.05 mm, which is on the order of the smallest neuromast, and presumably detected by the carp.

The key aspects of each flow measurement including maximum velocity, stagnation point location, and Kolmogorov length scale for each test is included in Table 1. The fine-bubble diffuser was tested at a restricted flow rate of 1 $Ls^{-1}m^{-1}$ to match with initial diffuser test with carp at the Aquaculture Center. The fine-bubble diffuser was also tested at 50 cm to see the effect of water depth on the physical fields. Note that the Kolmogorov length scale does not vary significantly between diffusers; however, the large scale velocity fields are slightly stronger using the fine-bubble diffuser.

**Table 1**
**Flow field characteristics of diffusers**

| Diffuser Type | Flow-rate ($Ls^{-1}m^{-1}$) | Depth (cm) | Maximum Velocity (cm/s) | Stagnation Point Location (X,Y) | Kolmogorov Scale (mm) |
|---|---|---|---|---|---|
| Fine-Bubble | 1 | 25 | 8 | (+/-1,0.6) | 0.08 |
| | 2.5 | 25 | 16 | (+/-1,0.75) | 0.05 |
| | 2.8 | 25 | 17 | (+/-0.8,0.6) | 0.06 |
| | 2.5 | 50 | 13 | (+/-1.5,0.75) | 0.07 |
| | 2.8 | 50 | 16 | (+/-2,0.75) | 0.05 |
| Coarse-Bubble | 2.5 | 25 | 12 | (+/-1,>0.8) | 0.05 |
| | 2.8 | 25 | 13 | (+/-1.5,>0.8) | 0.04 |

### 3.4 Sound Pressure Level

A basic understanding of sound properties and measurements techniques is important to review prior to presenting the results. A sound wave is a longitudinal wave, in which particles are displaced parallel to the direction of the motion of the wave (i.e. the particles oscillate locally). The frequency of the wave oscillations is one of the more prominent properties of sound, and is measured in cycles per second (Hz). The other prominent property of a sound wave is the acoustic pressure (*P*) or magnitude of the sound pressure wave. Acoustic pressure, generally reported in kPa, is merely the product of the particle velocity, speed of sound in a given medium, and the medium density; which is easily measured by electronic equipment such as hydrophones. The hydrophone captures a sound waveform which is viewed in the time-domain. A fourier transformation of the waveform allows the sound wave to be viewed in the familiar frequency domain, in which the amplitude of the sound wave is plotted dependently of individual frequencies. Once each sample is transformed, the average of four 10-sec samples is used to describe the sound at each measurement point. These plots also introduce the decibel (dB), a common unit of measure for sound pressure level (SPL). A decibel is a logarithmic ratio of the measured sound pressure amplitude to a reference pressure (for underwater measurements in this paper, ref. 1μPa. Figure 10 displays a typical SPL plot for background and with the diffuser on, while indicating key features of the sound signal.

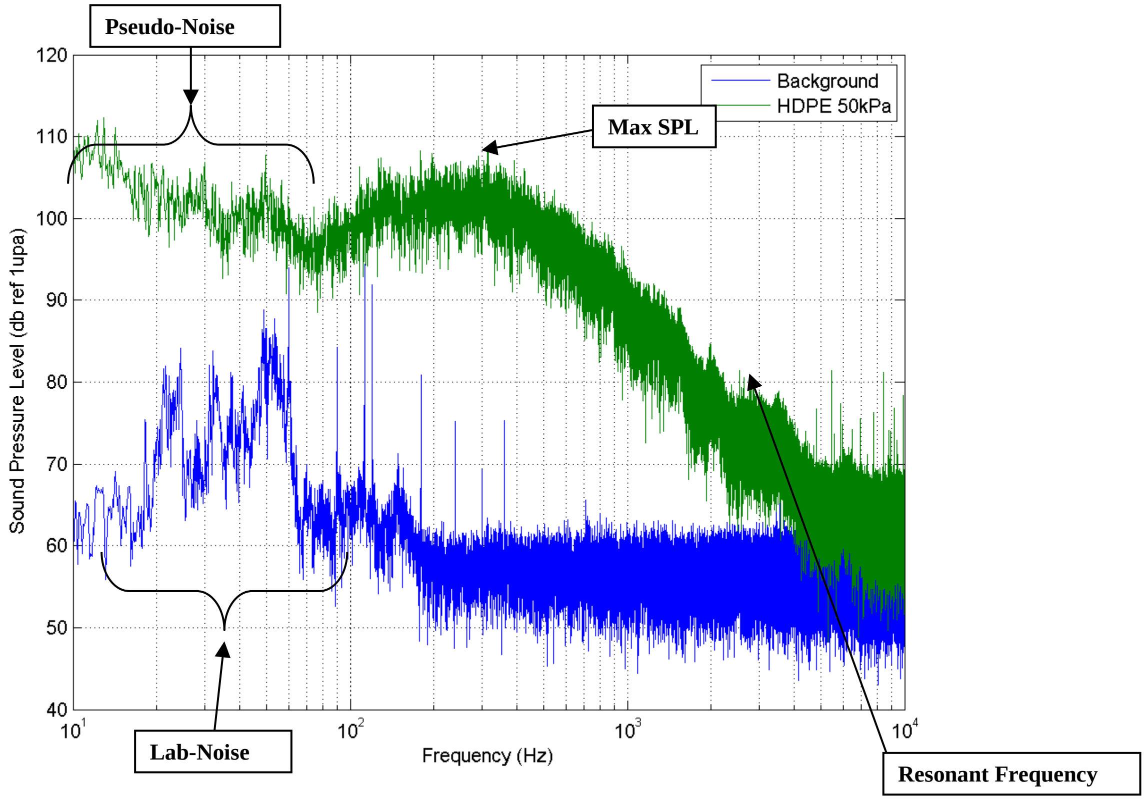



Figure 10.  Typical SPL plot, highlighting key features

The background sample was taken with no flow through the flume and most laboratory noise was isolated to less than 100 Hz.  The maximum SPL of 105 dB occurs at 300 Hz; while the SPL less than 100 Hz is mostly due to water motion noise on the hydrophone, and is classified as pseudo-noise.  The resonant frequency is a characteristic of the flume size, and indicates that any sound at a lower frequency cannot propagate within the flume (Akamatsu et al, 2002).

The audiogram for carp as presented by (Popper, 1972) indicates that the most sensitive region of hearing is between 100-500 Hz down to a SPL of 60 dB.  Another important factor to contend with is the “cocktail party” effect in which fish are unable to decipher a specific sound within their hearing range unless it is 10 dB above background levels (Popper and Carlson, 1998).  Note in Figure 10, the fine-bubble diffuser generates a sound approximately 40 dB greater than background noise at a particular location within the specified hearing range of carp.  Figure 11 provides a contour plot of the SPL above background for the fine-bubble diffuser at an air flow rate of 2.5 $Ls^{-1}m^{-1}$.  Note the sharp gradient of SPL in the x-direction away from the barrier and location of the 10 dB contour indicating a zone of influence.

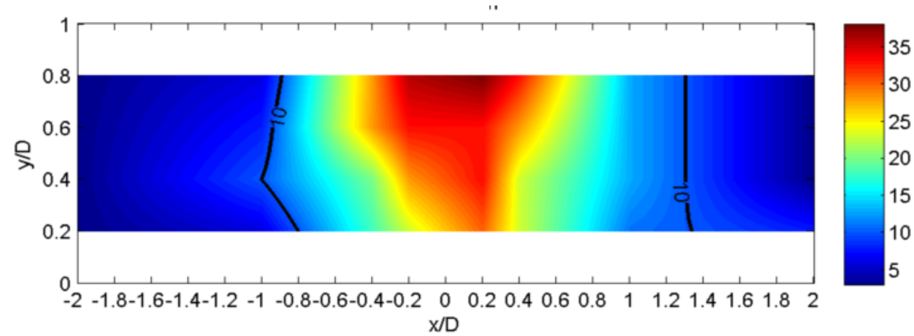



Figure 11.  SPL above background for fine-bubble diffuser at a depth D=25 cm (scale is in dB)

Figure 12 displays the SPL above background for the coarse-bubble diffuser at an air flow rate of 2.5 $Ls^{-1}m^{-1}$.

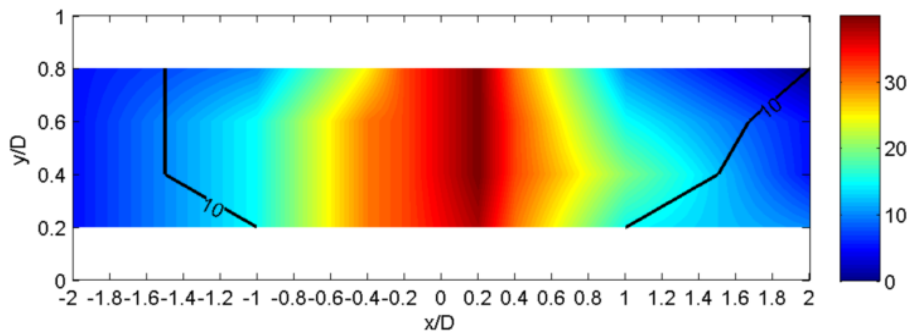



Figure 12.  SPL above background for coarse-bubble diffuser at a depth D=25 cm (scale is in dB)

It is important to note that sound measurements in a confined tank will vary from tests in an unconfined domain.  Low frequency sound is subject to a "cutoff phenomena" which states that sound at a frequency less than the cutoff frequency will attenuate rapidly; while a sound at a frequency higher than the cutoff frequency attenuates slowly, but may be subjected to scattering and absorption (Urick, 1975).  Attenuation is defined as a signal strength loss of 20 dB after a certain length, the attenuation length.  The cutoff frequency in a confined flume is equal to the resonant frequency of the flume, and Akamatsu (2002) demonstrated that sound at a frequency equal to the resonant frequency can theoretically propagate indefinitely.  Akamatsu also constructed theoretical formulas to predict the resonant frequency of a specific tank size and attenuation length for any frequency.  Figure 13 demonstrates the attenuation of a 500 Hz sound signal generated by the fine-bubble diffuser, at an air flow rate of 2.5 $Ls^{-1}m^{-1}$, plotted along with the theoretical attenuation.  Note approximately at a distance equal to one depth away from the diffuser, the signal has nearly vanished at all depths.

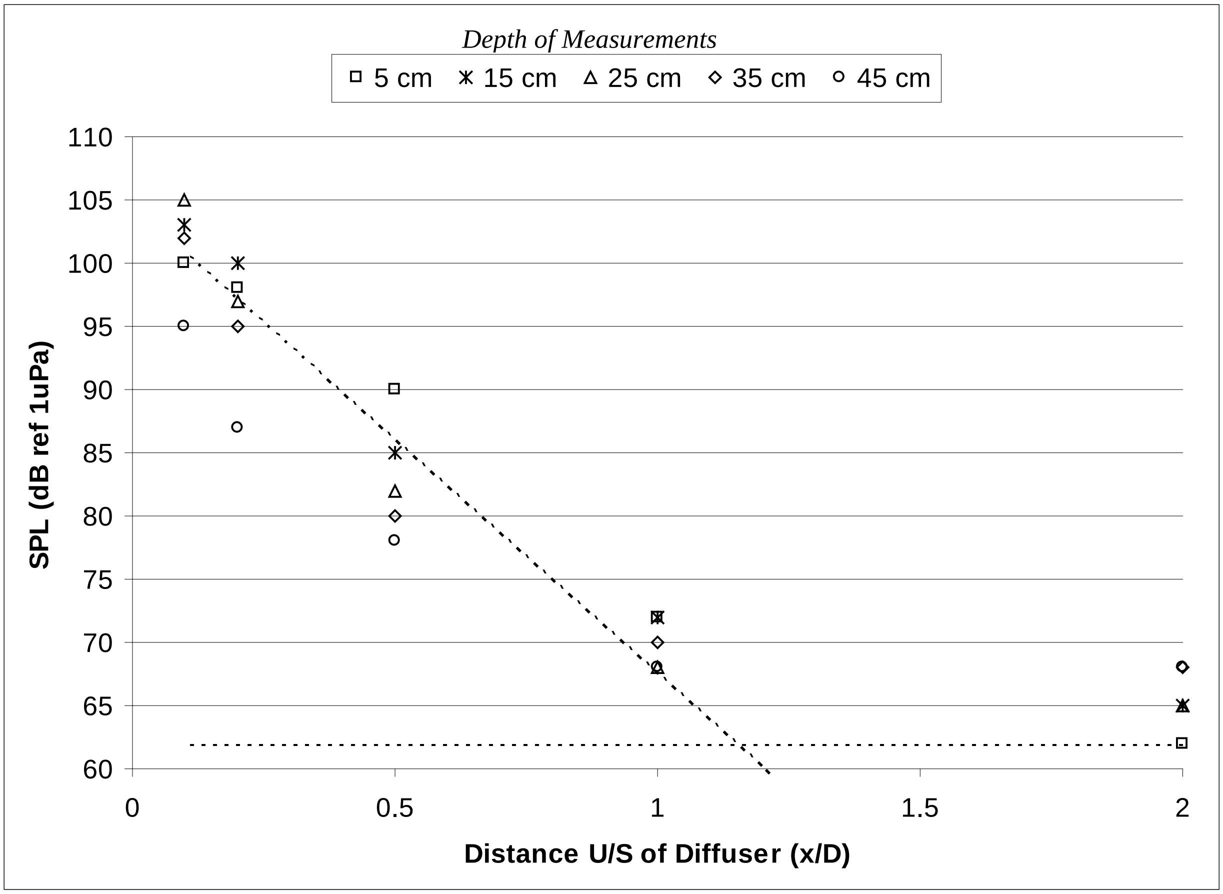



Figure 13. Attenuation plot for fine-bubble diffuser at depth D = 50 cm

The rapid attenuation of the primary sound signal is important to highlight, as this creates a natural gradient. Attenuation at the lower frequencies also prevents the sound generated from the barrier to be broadcast a significant distance upstream or downstream of the barrier, potentially allowing carp to acclimate to the sound.

Overall we quantified the acoustic field generated by each diffuser at varying flow rates and Table 2 provides the maximum SPL within 100-500 Hz and distance at which a 10 dB increase is experienced.

**Table 2**
**Maximum SPL of each diffuser**

| Diffuser Type | Flow-rate ($Ls^{-1}m^{-1}$) | Depth (cm) | Maximum SPL (dB) | Influence Distance (x/D) |
|---|---|---|---|---|
| Fine-Bubble | 1 | 25 | 90 | +/- 0.6 |
| | 2.5 | 25 | 100 | +/- 1.0 |
| | 2.8 | 25 | 112 | +/- 1.6 |
| | 2.5 | 50 | 98 | +/- 0.6 |
| | 2.8 | 50 | 110 | +/- 1.2 |
| Coarse-Bubble | 2.5 | 25 | 120 | +/- 1.6 |
| | 2.8 | 25 | 125 | > +/- 2.0 |

## 4.0 Developed Barriers

### 4.1 Mark I Barrier

The initial Mark I barrier tested at the Aquaculture Center was a single wand fine-bubble diffuser. The porous material utilized by the fine bubble diffuser is novel to bubble barrier designs based on the limited number of designs described in literature (Dawson et al., 2006; Taylor et al., 2005; Welton et al., 2002). Testing an individual wand served a dual purpose of being a starting point for barrier design and prototype experiment for the PIT tag detection system. Description of the pit tag detection system will be addressed in a later section. A electric air-compressor was used to supply air to the wand at a maximum rate of approximately 1.0 $Ls^{-1}m^{-1}$. A single wand at such a low pressure did not create a very robust barrier, resembling the typical aquarium air stone rather than impressive barrier. Upgrading the air supply to a gas powered air-compressor allowed a maximum sustained air-flow rate of 2.5 $Ls^{-1}m^{-1}$, similar to that tested at SAFL. Figure 14 provides the top view of single fine-bubble diffuser at an air-flow rate of 2.5 $Ls^{-1}m^{-1}$. The acoustic field generated by the Mark I barrier was confirmed with hydrophone measurements to be similar to that studied at SAFL.

Figure 14.  Top view of Mark I barrier at 2.5 $Ls^{-1}m^{-1}$

The Mark I barrier appears to have retarded carp movement but not limit the number of passages through the barrier.

### 4.2 Mark II Barrier

Due to the relatively minimal effect of the Mark I barrier on carp movement, a sizable increase in dimension, gradient, and air-flow rate was integrated into the design of the Mark II barrier.  The design of the Mark II barrier also focuses on the hypothesis that the acoustic field is the primary agent for limiting carp passage; therefore, a gradient of SPL was created in the downstream direction by using a combination of different diffusers. The Mark II diffuser consists of the following (looking up- to down-stream): one fine-bubble diffuser supplied by gas-powered compressor, four coarse-bubble diffusers supplied by regenerative blowers, and one ultra-coarse diffuser (3 mm diameter holes spaced at 5 cm) also supplied by regenerative blowers.  Figure 15 provides a diagram of the Mark II barrier configuration.

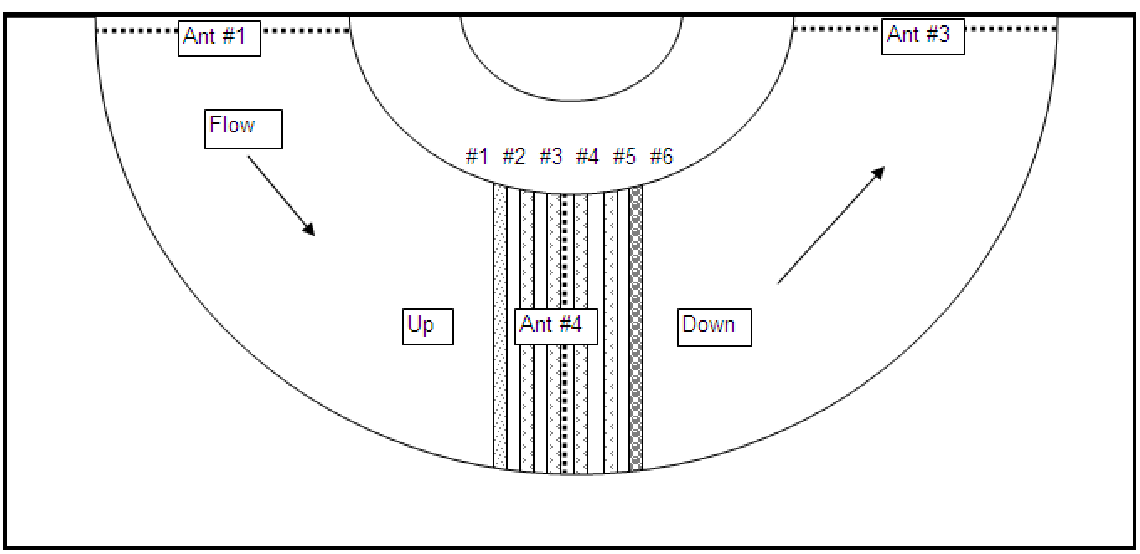



Figure 15.  Diagram of the Mark II barrier in the Aquaculture Center

The air-flow to diffuser #2 to #5 is controlled by a PVC manifold capable of directing the quantity of air to each diffuser. The regenerative blowers are capable of supplying greater amounts of air at low pressures. The total air-flow rate supplied to the entire Mark II barrier is 31.5 $Ls^{-1}m^{-1}$, approximately a 10 times increase of the Mark I barrier. The Mark II barrier thickness also increased from approximately 10-15 cm to almost 1 m.

The SPL generated by the barrier without the fine-bubble diffuser was measured by placing the hydrophone 10 cm upstream of #2 (indicated as US) and 10 cm downstream of #6 (indicated as DS). While maintaining the location of the hydrophone constant, multiple combinations of diffusers were tested to find the optimal sound field. Figure 16 presents the SPL at 150 Hz 10 cm up- and down-stream of the diffusers incrementally adding or removing selected diffusers.

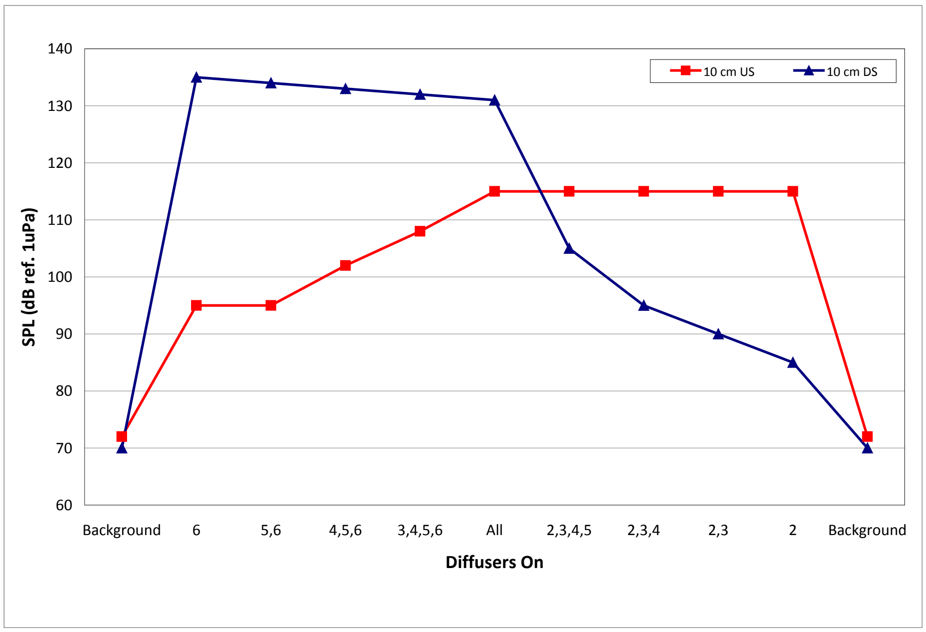



Figure 16. SPL of Mark II barrier without fine-bubble diffuser

Note the maximum SPL of 135 dB occurs only when the ultra-coarse diffuser is supplied all the air; however, only a 4 dB decrease is observed when the air is distributed between all 5 diffusers. The constant SPL generated near the edge of the barrier indicates that the SPL on the up- and down-stream sides of the barrier is controlled by each respective exterior diffuser. We selected the optimal setting to be full air supplied to all diffusers, as this creates the strongest SPL throughout the entire barrier. Adding the fine-bubble diffuser is expected to increase the complexity of flow fields, and extend the SPL on the up-stream side of the barrier at 100 dB. Figure 17 provides a top view of the Mark II diffuser with and without air supplied.

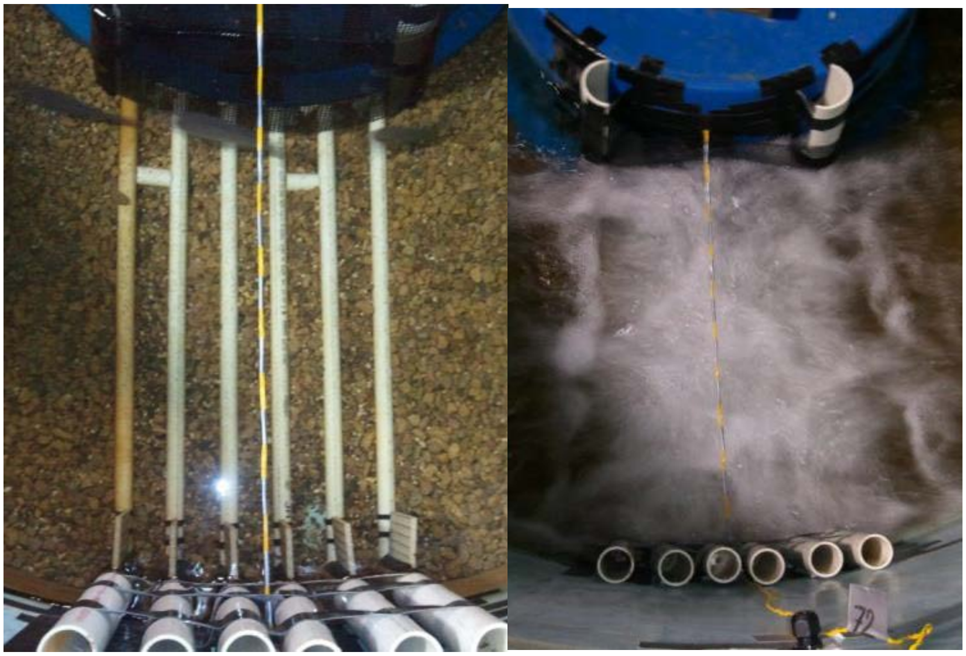


Figure 17.  Top view of Mark II barrier without (left) and with air (right)

### 4.3 Mark III Barrier

The Mark III barrier was designed to maximize the air-supply equipment available at the Aquaculture Center; this also corresponds to a maximum air-supply that can be effectively scaled-up to an existing channel.  The design of the Mark III barrier focuses on the hypothesis that the acoustic field is the primary agent for limiting carp passage as the velocities generated by the bubble barrier are not significantly greater than naturally occurring velocities in a flashy stream.  In contrast to the Mark II barrier, the Mark III barrier is characterized by a constant air flow over a uniform barrier; therefore, the SPL is constant from the up-stream to down-stream sides.  Figure 18 displays the typical layout of the Mark III barrier.  The Mark III barrier consists of PVC pipe containing ultra-coarse holes (3 mm diameter holes spaced at 2.5 cm) with a pipe grid spacing of 12.5cm X 16.5cm.  The ultra-coarse holes were selected to provide the highest SPL while not reducing the air-pressure to a point of non-uniform bubble curtains.  The PVC grid is separated into four individual quadrants, each supplied by a single regenerative blower. The total air-flow rate supplied to the entire Mark III barrier is 108 $Ls^{-1}m^{-1}$, approximately a 3 times increase of the Mark II barrier.  The Mark III barrier thickness remained consistent with the Mark II barrier at 1m.  An interesting feature of the Mark III barrier is the individual cells of bubble curtains created by the grid layout.  The bubble cells provide a labyrinth configuration of curtains that removes any gaps that carp could possible navigate through, i.e. the carp must pass through a bubble curtain.

Figure 18. Mark III configuration without (left) and with (right) air supplied

The SPL generated by the barrier was measured by placing the hydrophone 10 cm upstream and 10 cm downstream of the barrier. The maximum SPL generated up- and down-stream is approximately 124 dB, which is approximately 40 dB higher than background. The SPL was also measured in the rear section of the tank to be 85 dB, which at less than 10 dB above background falls within the “cocktail party” effect and should be undetected by carp. The Mark III barrier does not have an equivalent SPL field as the Mark II, approximately 10 dB drop on the down-stream side and 10 dB gain on the up-stream side. Maximum SPL reduction is the result of reduced blower efficiency and greater demand of air in each diffuser quadrant.

## 5.0 Environmental Effects of Bubble Barriers

The objective of this phase was to study how environmental effects (i.e. flow and depth) modify the physical fields generated by the bubble barrier. The bubble barrier was designed to reduce recruitment of juvenile carp from nursery lakes to stable bodies of water, by being placed within the small interconnecting channels between water bodies. These channels have typical dimensions of <0.5m deep and 1-3m wide and usually experience seasonal flooding, The diminutive size of the channel and shallow water makes most current barrier technologies unattractive. A bubble barrier should be ideal for this application as the bubble curtain does not require human control to adjust to rapidly varying conditions. Understanding how the physical fields generated by the bubble barrier are affected by changes in flow and depth should provide insight into a safe operating range that these barriers can be effective.

The final portion of this section outlines the design of the third bubble barrier tested under the same behavioral tests as in **Results 1 and 2**. The design and complimentary measurements associated with the Mark III barrier are included. Results of the carp behavioral tests are provided in **Results 2**.

## 5.1 Variations in Flow Depth

Relatively narrow channels are prone to large fluctuations in flow depth during high flows as a means to increase flow capacity, so the first variable we studied for effects of barrier performance was depth. In **Results 1** we quantified the physical fields generated by a fine- and coarse-bubble diffuser in 25cm, and 50cm of water. In the previous section, Table 1 and Table 2 provide the characteristic magnitude of the velocity field and sound pressure level (SPL). A close inspection of these results reveals that an increase in depth from 25cm to 50cm does not greatly affect the strength of flow or acoustic fields. The fine -bubble diffuser at $2.5Ls^{-1}m^{-1}$ and $2.8Ls^{-1}m^{-1}$ air flow rate saw a reduction in the maximum velocity of ≈15% when the depth was increased to 50cm. The SPL for the same settings only experienced ≈2% reduction in magnitude. A reduction in velocity magnitude was expected as the increased depth provides more dissipation to the flow fields. The maximum SPL does not change as the acoustic input does not change between experiments and the maximum SPL occurs right next to the diffuser openings.

A significant change in the sound field does occur as a result of the increased depth. Sound attenuates so rapidly in water less than 1m deep that any change in depth will greatly affect the SPL gradient. This phenomenon is demonstrated by the relatively large change in attenuation length for a similar sound signal in 25cm and 50cm deep water. At 150 Hz, the attenuation length is 17cm at a depth of 25cm and 26cm for a depth of 50cm. Essentially this illustrates that in 25cm of water a sound signal loses strength at a rate 35% faster than in 50cm of water, increasing the SPL gradient. The increase in the sound gradient due to shallow water is important to note as sharp physical gradients are key to the barrier design, as they may elicit a more immediate avoidance response from the carp.

## 5.2 Variations in Flow Velocity

The behavioral tests in **Results 2** were performed under current velocities ≈5cm/s. The flow was selected to minimize the effect of current on the bubble curtain, while still providing an overall flow direction to motivate carp movement. This flow is less than expected in real field sites, and higher flows were investigated to determine how they modify the bubble barrier. Flow data is often not available for the outlets of nursery lakes due to their remote location; however, limited flow data was collected by the Sorensen Lab Group, from the University of Minnesota, on nursery lakes in central Minnesota. Their data indicated that velocities in the typical interconnecting channel range from 10cm/s to 1m/s, with the mean velocity ≈20cm/s. We quantified the physical fields generated by a single fine- and coarse-bubble diffuser under 10cm/s and 20cm/s.

Bubble curtains are driven by a buoyancy force pushing a group of bubbles towards the surface of the water. Bubbles greater than 1mm in diameter have a constant rise velocity between 25cm/s and 30cm/. Under the influence of flow normal to the bubble curtain, the bubble curtain is expected to undergo some angular deformation θ, as shown in Figure 19.

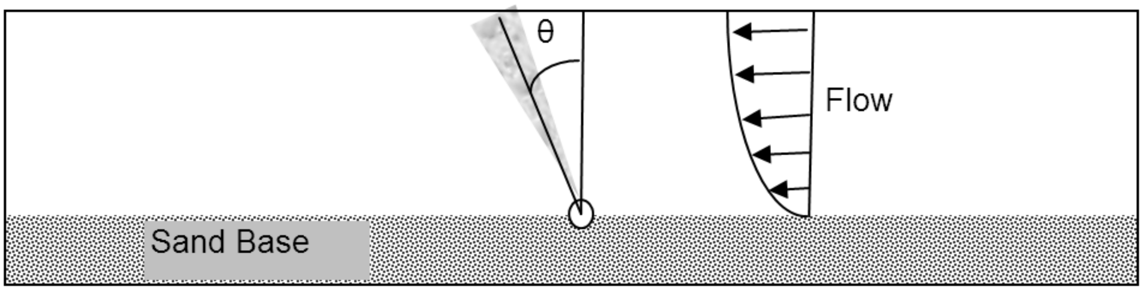



Figure 19. Angular deformation of bubble curtain under normal cross flow

Using basic trigometry, it is clear that θ≈45° when the depth average velocity is equal to the rise velocity. A channel velocity greater than 30cm/s will deform the bubble curtain so the longitudinal reach of the bubble curtain becomes much greater than the depth of flow, effectively stretching the bubble curtain.

### 5.2.1 Flow Measurements

We calculated the time-averaged velocity vector at various locations along the centerline of the SAFL flume with the fine- and coarse-bubble diffusers under approximately 10cm/s and 20 cm/s cross flow. From the velocity vectors we calculated the streamlines (the line tangent to the local velocity vector) for each given diffuser set-up. In the interest of brevity, we will present the physical field measurement results for the 20cm/s flow as they display a more pronounced change in flow and SPL patterns. Figure 20 provides the velocity vector plot for the fine-bubble diffuser at an air flow rate of 2.5 $Ls^{-1}m^{-1}$ and set at a depth of 0.25 m. Figure 21 provides the corresponding streamline plot to the velocity vectors plotted in Figure 20. The streamline plot is included to highlight the location of the stagnation point, or center of rotation of the recirculation cell. Note, the x- and y-axis have been normalized by the depth of flow.

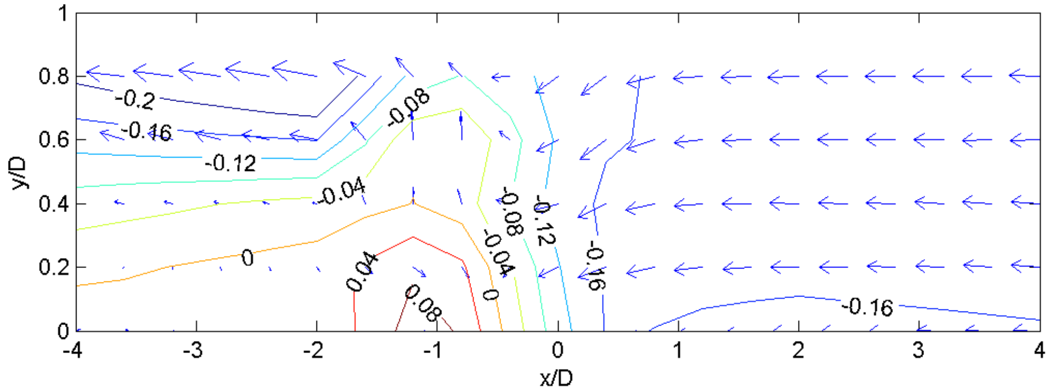



Figure 20. Velocity field for fine-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm under 20cm/s cross flow (velocity contours are in m/s)

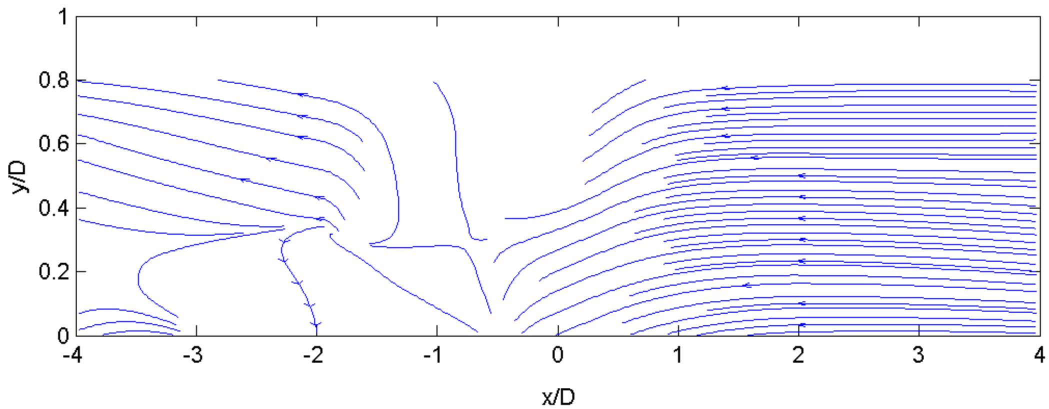



Figure 21. Streamline plot of velocity field generated by fine-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm under 20cm/s cross flow

Note that the stagnation point (point of zero velocity) can only be identified on the downstream side of the barrier between x/D=-2.5. This is significantly different than the location found under no flow conditions (x/D = +/-1). Figure 22 provides the velocity vector plot for the coarse-bubble diffuser at under the same conditions. Figure 23 provides the corresponding streamline plot to the velocity vectors plotted in Figure 22.

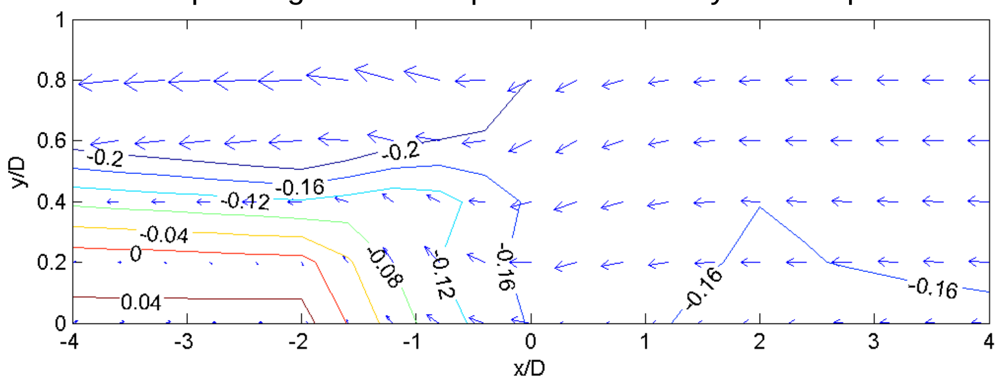



Figure 22. Velocity field for coarse-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm under 20cm/s cross flow (velocity contours are in m/s)

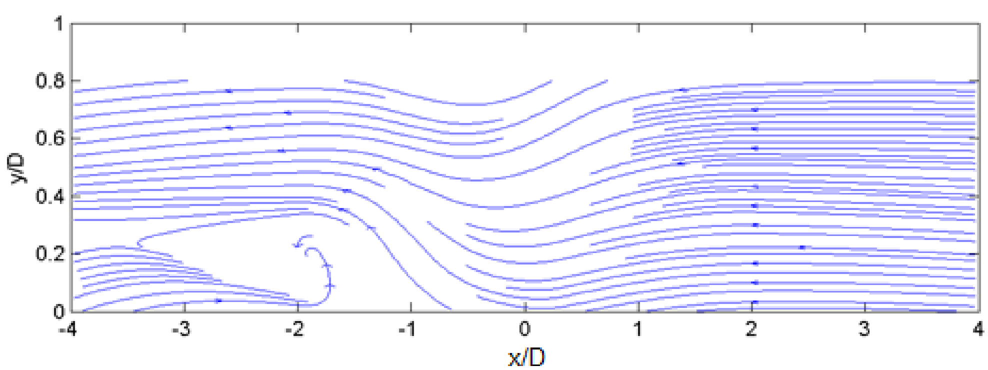



Figure 23. Streamline plot of velocity field generated by coarse-bubble diffuser at 2.5 $Ls^{-1}m^{-1}$ and a depth D=25cm under 20cm/s cross flow

Note the stagnation point is located in approximately the same location as the fine-bubble diffuser. The fine-bubble diffuser clearly creates a strong upward plume in the proximity of the bubble curtain, while the coarse-bubble diffuser appears to have dissipated flow strength near the surface (velocities down-stream of the curtain are equal to background flow). During each flow test, the angular deformation was calculated for each diffuser and compared to expected values presented in Figure 24. The expected angular deformation is calculated as follows:

$$\theta = 90° - \tan^{-1}\left(\frac{L_{rise}}{L_{long}}\right) \qquad (1)$$

Where

$L_{rise}$ = vertical distance traveled by bubbles (depth of water)

$L_{long}$=longitudinal distance traveled in time required for bubbles to reach the surface

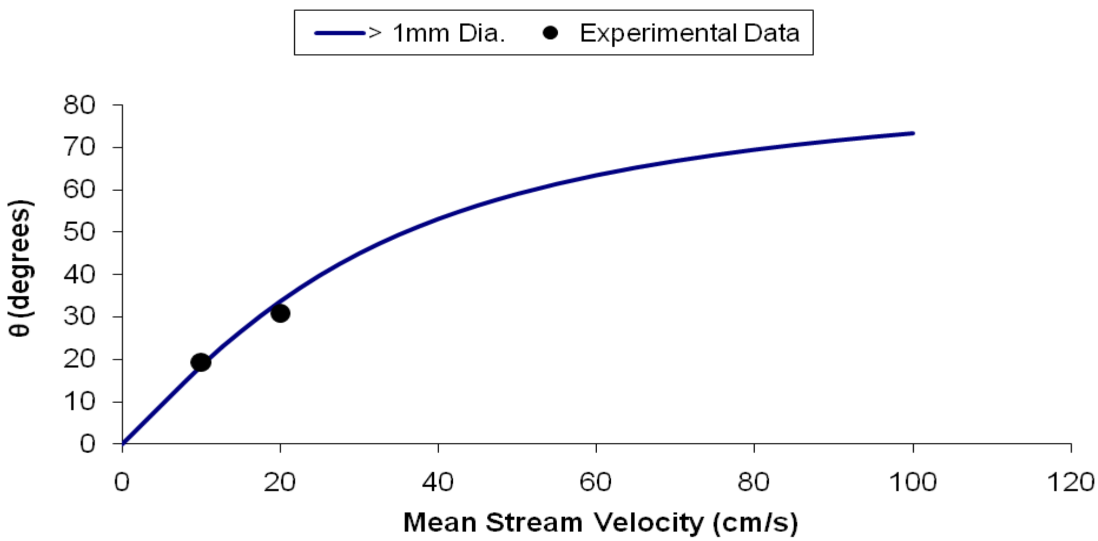



Figure 24. Expected deformation angle of bubble curtain with experimental data provided

Note the close agreement of experimental data and the expected deformation. The deformation did not change with respect to the bubble size, confirming that bubbles >1mm in diameter will rise at approximately the same velocity.

## 5.3 Acoutic Measurments

Based on work by Tonolla et al. (2009), sound generated by flow is expected to increase as velocity increases due to increased turbulence. Increased background sound levels increase will decrease the SPL above background, decreasing the range of influence due to sound of the barrier. Tonolla et al. (2009) showed that turbulence created by flow around in-stream objects generates significant underwater noise; however the sound attenuates quickly due to shallow water losses discussed earlier.

Based on the assumption that the barrier would be placed in a location acceptably away from flow obstructions, background noise should be reduced. Applying a uniform flow across each barrier sans flow obstructions, we obtained the increased background SPL due to flow through a channel. The experimental background levels are expected to be similar to field conditions as the barrier would ideally be placed within a control section free from flow obstructions. The background SPL due to 10 cm/s and 20 cm/s flow was 70dB and 75dB (between 100-500Hz), respectively. This represents only an increase in background noise as the background SPL under no flow was 62dB (between 100-500Hz).

We measured the SPL field generated by a fine- and coarse-bubble diffuser under 2.5Ls$^{-1}$m$^{-1}$ air flow rate under 10cm/s and 20cm/s flow. Sound pressure waves propagate at a velocity much greater than the flow velocity (i.e. 1500m/s vs. 20cm/s), so the magnitude of the sound field is not expected to be affected by flow. Figure 25 and 26 provide a contour plot of the SPL above background for the fine- and coarse-bubble diffuser, respectively, at an air flow rate of 2.5 Ls$^{-1}$m$^{-1}$ with 20cm/s flow.

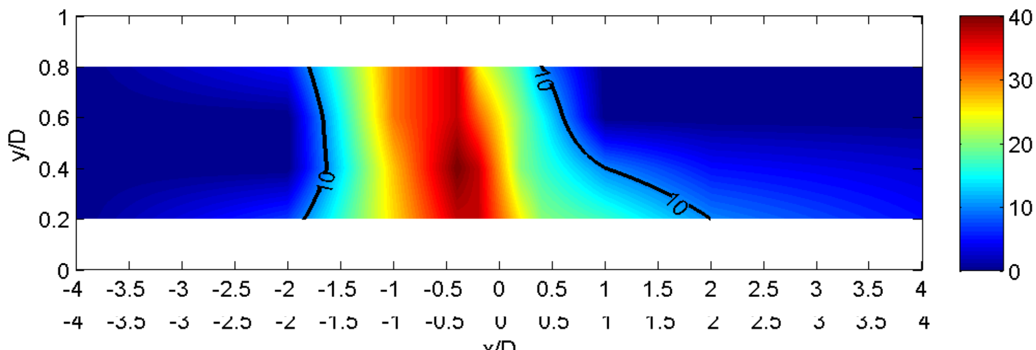



Figure 25. SPL above background generated by the fine-bubble diffuser at 2.5 Ls$^{-1}$m$^{-1}$ and a depth D=25cm under 20cm/s cross flow

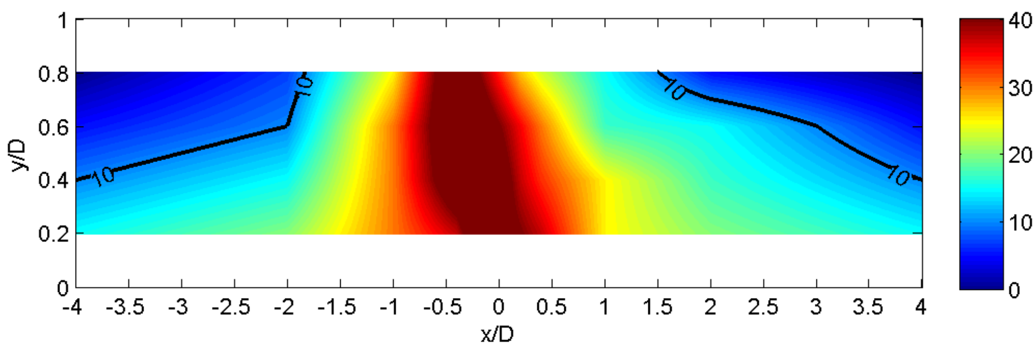



Figure 26. SPL above background generated by the coarse-bubble diffuser at 2.5 Ls$^{-1}$m$^{-1}$ and a depth D=25cm under 20cm/s cross flow

Note the maximum SPL has a down-stream facing deformation, as noted in Figure 24. The resulting angle of deformation in the sound field is a result of anisotropy of sound attenuation along the bubble curtain. Manasseh et al. (2004) demonstrated that sound propagates along a bubble chain more efficiently than normal to it; indicating that for a sound source (diffuser) at the bottom of the channel, the peak sound intensity will match the location of the bubble curtain. Longitudinal stretching of the maximum SPL may not decrease the effectiveness of the barrier to stop carp, as Figure 25 and 26 clearly show a vertically continuous sound gradient well within the carp hearing range. However, it should be noted that the sound gradient may not be vertically continuous if the cross flow is sufficiently strong to break-up the bubble curtain enough to disrupt the propagation of sound along the curtain. Based on the SPL field created under 10cm/s and 20cm/s, the bubble curtain is not expected to see an decreased performance for flows less than the bubble rise velocity of 30cm/s. Further tests would need to be performed for flows much greater then 30cm/s.

## 6.0 Acoustic Barrier

The objective of this phase was to study how the acoustic fields generated by a bubble barrier could be recreated by underwater speakers. Our earlier observations from have led us to hypothesize that the acoustic field generated by bubble barriers is the main deterrent to juvenile carp. To test this hypothesis, an acoustic-only barrier driven by underwater speakers was constructed to use in similar behavioral tests. Before testing the barrier on carp, an investigation of how a similar acoustic field may be generated by underwater speakers was performed. This section outlines the design of the speaker barrier and the measured acoustic fields generated.

### 6.1 Speaker Barrier Design

The speaker barrier system consists of two University Sound UW30 underwater speakers driven by a InterM A-120 amplifier. A 10s sound sample recorded from the Mark II barrier tests at the Aquaculture Center was selected as the sound signal for the speaker barrier. The computer program WavePad Sound Editior, was used to loop the sound sample continuously without interruption. Figure 27 provides the typical waveform of the sound sample, with magnification of the sample at the 1s and 0.1s scales.

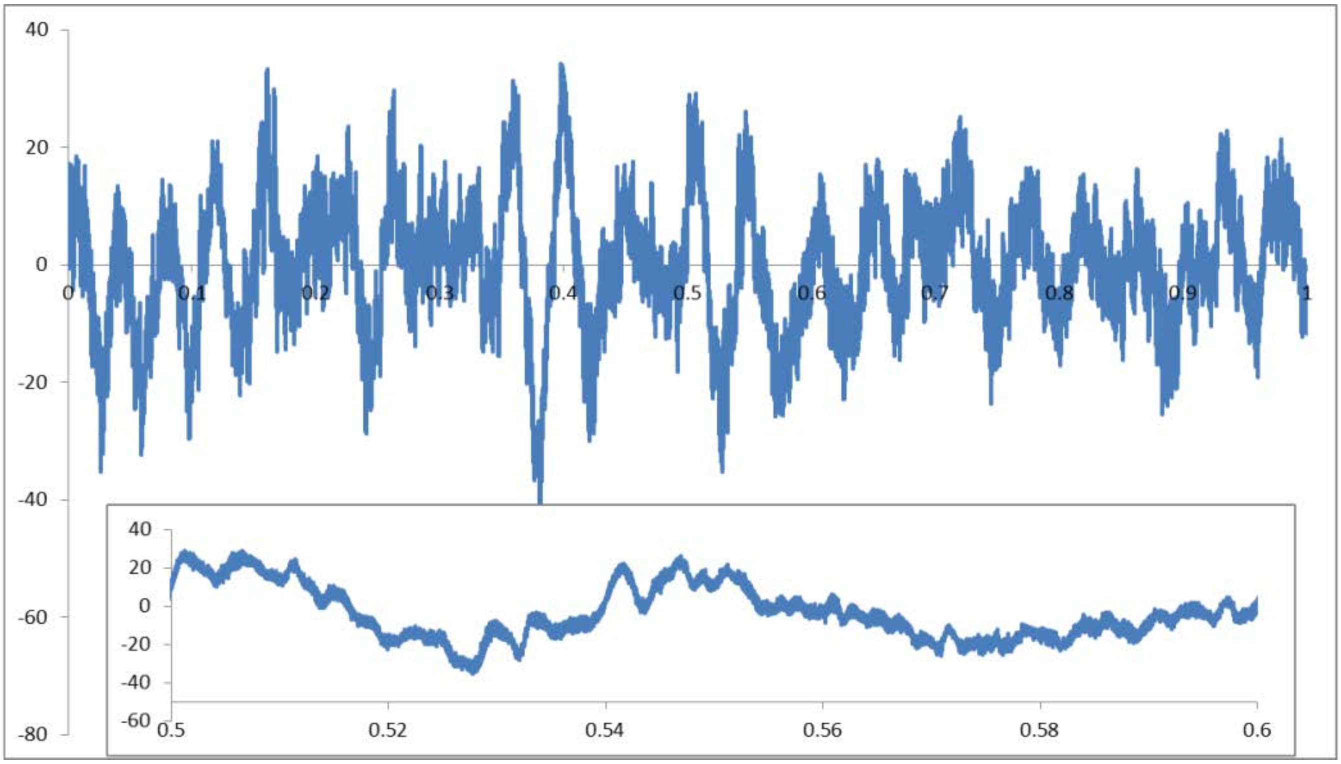



Figure 27. Waveform of sound sample played through underwater speakers at 1s and 0.1s scales.

The sound sample included in Figure 1 has a peak frequency of 150 Hz, typical of most recorded signals for Mark II and Mark III barriers. The minimum amplitude nearest the speakers was set to approximately match the maximum SPL recorded for the Mark II barrier, 130 dB (ref 1 µPa). The speakers were encased in plexiglass boxes to protect and position the speakers.

### 6.2 Acoustic Measurements

The main goal of the testing is to quantify how the acoustic field generated by a speaker, using a sound signal from the bubble barrier, mimics the acoustic field generated by the Mark III bubble. The amplifier was used to fine tune the speaker output to reach an approximate SPL of 130 dB (ref 1 µPa) at a location 10cm above the centerline of the speakers; however, the speaker system was capable of generating a maximum SPL of 150 dB (ref 1 µPa). Figure 28 provides the SPL contours above background for the speaker barrier system on the upstream side of the barrier (speakers located at X/D=0).

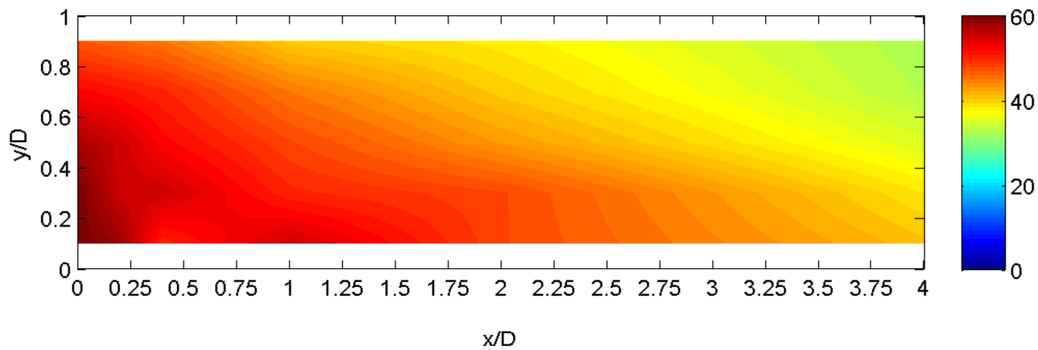



Figure 28. SPL above background generated by the speaker barrier with a depth D=25cm under 0cm/s cross flow

The sound gradient away from the speakers through the centerline of the flume is more gradual than that created by the bubble barrier. A potential cause for this discrepancy is that the bubble barrier supplied sound from a continuous line source (i.e. holes in diffuser) versus two large point sources (i.e. speakers). Using two speakers created more complexity in the sound field around the barrier, resulting in a more gradual observed acoustic gradient. Figure 29 displays the cross-sectional SPL contour through the center of the speakers, and at cross-sections upstream of the speakers. Note the SPL peaks directly above the speakers at X/D=0. The interaction of the two peaks, moving away from the speakers, creates a complex sound field not observed in the bubble barrier tests. Also note that the maximum SPL at X/D=2.0 is along the sides of the flume due to refraction of the sound waves.

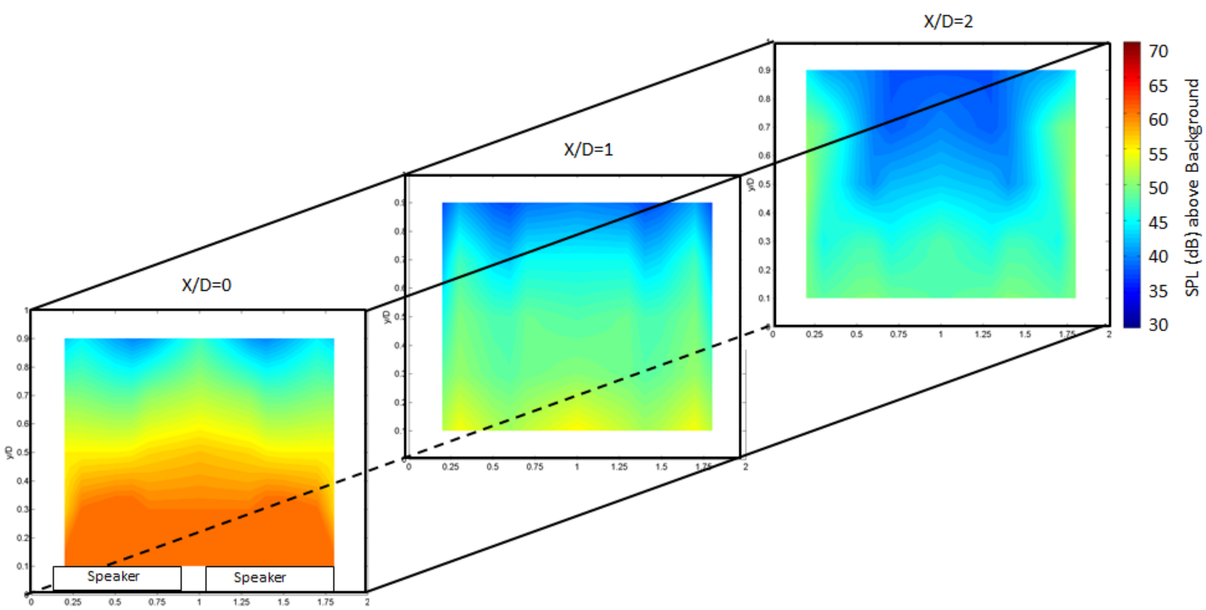



Figure 29. Cross-sectional profile of SPL above background generated by speaker barrier

Bubbles have been shown to increase broadband noise attenuation by 5-10dB (re 1µPa) (Nehls *et al.* 2007) and could be used in conjunction with speakers to increase the acoustic gradient near the bubble curtain. In an attempt to increase the acoustic gradient associated with the speaker barrier, a trial was completed with a fine bubble diffuser placed 25cm upstream of the speakers. Figure 30 provides the SPL contours above background for the speaker barrier system with a fine-bubble diffuser placed at X/D=1 at an air flow rate of 2.5 $Ls^{-1}m^{-1}$. Note the SPL contours differs greatly from that in Figure 29 at Y/D>0.5. Immediately downstream (X/D <1) of the bubble barrier a distinct increase in SPL and a steep gradient through the bubble curtain was observed. The maximum attenuation caused by the bubbles occurs where the curtain is at its thickest point at approximately 80dB/m. Near the bottom no attenuation was observed, indicating that the sound attenuation is dependent on the width of the bubble plume .

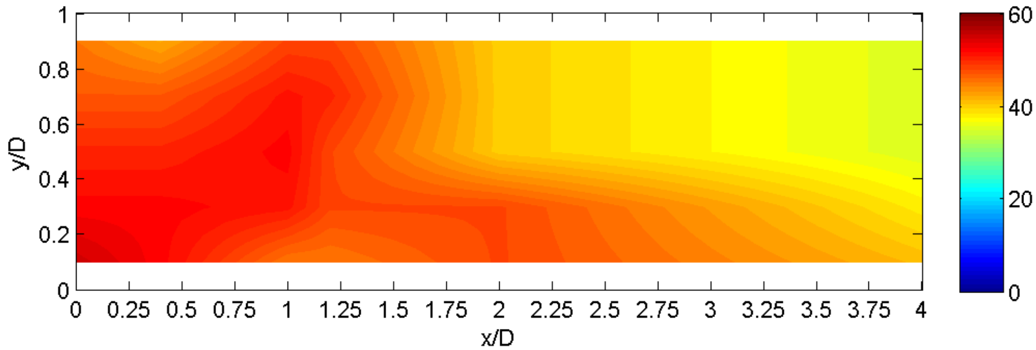



Figure 30. SPL above background generated by the speaker barrier with fine-bubble diffuser placed at X/D=1 (depth D=25cm and 0cm/s cross flow)

Despite the different sound gradient generated by the speakers, the acoustic-only barrier should suffice to test our acoustic deterrence hypothesis. The speaker-bubble barrier behavioral trial would represent an improved iteration of the bubble barriers previously tested, and should be completed based on the results of the speaker-only barrier.

**Result 2:** Laboratory Investigation: Biology

**Description:** The objective is to determine whether bubble curtains produce sensory stimuli that can impede the directed movement of juvenile invasive common carp. Biological work will proceed in three steps: i) Determining if a bubble curtain can impede carp from moving either down- or up-stream in a laboratory flume running at a typical field depth; ii) Determining what sensory field is responsible for this impediment ; iii) Determining how to optimize this field(s) to impede carp movement in a laboratory flume.

| | | |
|---|---|---|
| **Summary Budget Information for Result 2:** | **Trust Fund Budget:** | **$110,300** |
| | **Amount Spent:** | **$110,268** |
| | **Balance:** | **$ 32** |

| Deliverable | Completion Date | Budget |
|---|---|---|

| | | |
|---|---|---|
| **1.** Testing and documentation of the effectiveness of bubble curtains to impede the movement of juvenile carp in a laboratory flume.<br>Questions:<br>What is level of deterrence? Why does the curtain it deter movement? How can it the repulsive effects be optimized | 6/30/13 | $110,300 |

**Completion Date:** *6/30/2013*

**Final Report Summary**

## 1.0 Fish Tracking System

The key component of the Aquaculture Center testing is the controlled experimental environment which tracks fish movements automatically through the use of radio frequency identification (RFID) PIT tags. A PIT tag consists of a microchip that contains a unique identification number that can be detected/recorded passively when passing through a specifically tuned antenna. Each antenna is made of wire wound in loops and connected to tuner boxes, which are in-turn connected to a reader. The reader sends out a signal that allows each individual antenna to detect if a PIT tag is within its sensing range. The sensing range can be manually adjusted via wire thickness, number of loops, and fine tuning of the tuner box. The antenna used in the experimental tank have a reading range at approximately 1.0 meter, meaning a PIT tag with in 0.5 m up- or down-stream of the antenna will be detected. Four antennas are evenly spaced around the test tank as seen in Figure 1. The antennas are numbered sequentially 1 through 4.

The reader logs all detections onto a memory card which is downloaded via computer program Procomm Plus. Each detection log includes the date, time, PIT identification number, length of consecutive detections, and location of detection, from which we can calculate how many times a carp passes in an up- or down-stream direction (i.e. 1-4-3 or 3-4-1). The Mark I barrier configuration used three antennas, with the barrier located between two as seen in Figure 1. The Mark II barrier configuration uses four antenna with the #4 antenna located directly over the barrier.

The PIT tag is inserted into the body cavity of randomly selected carp. Only one PIT tagged carp is allowed in the test tank at a time, as multiple PIT tags cancel each other if in the same detection range simultaneously. The only way a PIT tag will not be detected, once the system is tuned correctly, is if the tag is oriented within 10 degrees of parallel to the antenna. Through the Mark I and II barrier tests, the PIT tag system has captured 99% of all possible detections.


Figure 1. Typical experimental tank for behavioral tests

## 2.0 Fish Testing Protocol

A strict testing protocol is paramount to reduce the number of variables that could influence carp behavior during a given testing period. Following the experiments by Zydlewski et al. (2005), our tests will be carried out at the Aquaculture Center in a circular tank with PIT tag antenna evenly spaced in the channel. A moderate flow of 5 cm/s is generated in a counter-clockwise direction by a freshwater input. Water is continuously cycled through a re-circulation system via a drain separated from the fish by the central tank as seen in Figure 1. All experimental carp were caught in the wild by electro-fishing. All fish are maintained onsite in four separate tanks onsite; a separate tank for tagged/untested, tagged/tested, untagged/untested, and untagged/tested carp. All tanks are kept in relative darkness by placing tarps overtop and water is continuously re-circulated. The carp are fed pellets once a day at approximately 10:00 am. Water temperature is maintained at approximately 21 degrees C in all tanks, to reduce any undue stress on the fish during testing.

All tests are carried out in complete darkness to remove any visual influence of the bubble curtain; tests occur between the hours of 10:00 PM and 6:00 AM, with a tarp covering the test tank and all lights off in the laboratory. An attempt is made to randomly select fish from the untested populations, so as to generate independent results. Each test consists of selecting one PIT tagged fish and two untagged fish and placing them in the test tank. The first 10 minutes of each test is considered acclimation time, and not included in the data analysis. The test period encompasses the following 7 hours of detections. During the tests, all extraneous electrical systems are turned off, to reduce noise detected by the antenna. For every test completed with air supplied to the barrier, one control test is completed. A control test consists of using a new group of fish in the test tank with the barrier in place, but not supplied air. Once the testing is complete, all fish are weighed and measured for total body length. The fish are then separated into the holding tanks with tested fish, for future tests. No fish is used in the test tank twice throughout the barrier on, or corresponding control, test for a given barrier type.

The detections are analyzed using the computer program Matlab and MS Excel to calculate the number of passages over the barrier, average passage time, number of detections at the barrier, and average time spent near the barrier. Due to the limited size and large variability in the data sets, the probability reported in the following sections is a result of the Mann-Whitney U test.

## 3.0 Barrier Test Results

### 3.1 Mark I Barrier

The Mark I barrier tests have a dual objective of prototyping the PIT tag detection system and as a starting point for the barrier designs. The Mark I barrier was supplied an air-flowrate of 1.0 and 2.5 $Ls^{-1}m^{-1}$. A total of four control tests, four barrier tests with 1.0 $Ls^{-1}m^{-1}$, and two barrier tests at 2.5 $Ls^{-1}m^{-1}$. A limited number of tests were completed due to issues with high fish mortality. The PIT tag system preformed well over all tests, limiting the number of missed detections to less than 1% of all detections. Detections are considered missed when the carp is detected at two non-consecutive antennas. All control tests indicate a strong tendency for the carp net movement to be downstream, which is expected when as the carp cannot orient to the substrate in the darkness. Figure 2 and 3 provide the total up- and down-stream passages over the barrier for the control at two flow rates. Note that there is a slight decrease in movements when the barrier is on in both directions, but is not statistically significant. Also note that all bar graphs are provided with standard error bars.

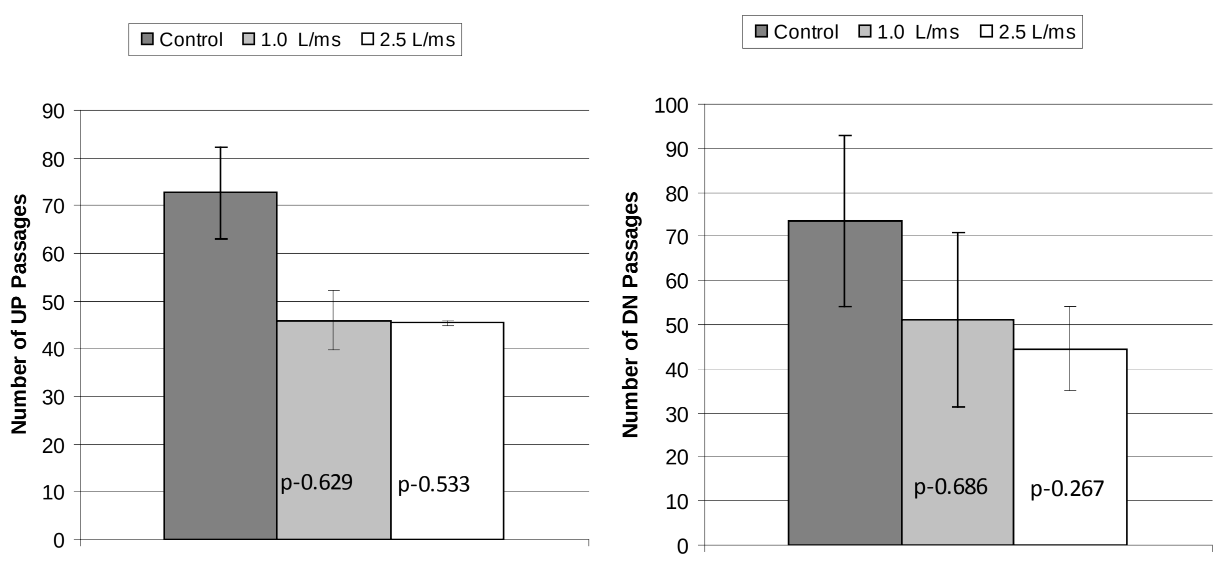



Figure 2. Number of up-stream (left) and downstream (right) passages over the Mark I barrier at 1.0 and 2.5 $Lm^{-1}s^{-1}$

Figure 3 provides the mean time required to pass over the barrier during the control and two flowrates. Note that the passage time increases for the barrier on configurations, and is statistically significant with $p < 0.05$. The limited number of tests restricts the statistical significance of these results; however, the barrier tests indicate that the Mark I barrier may retard carp movement by approximately 10 seconds.

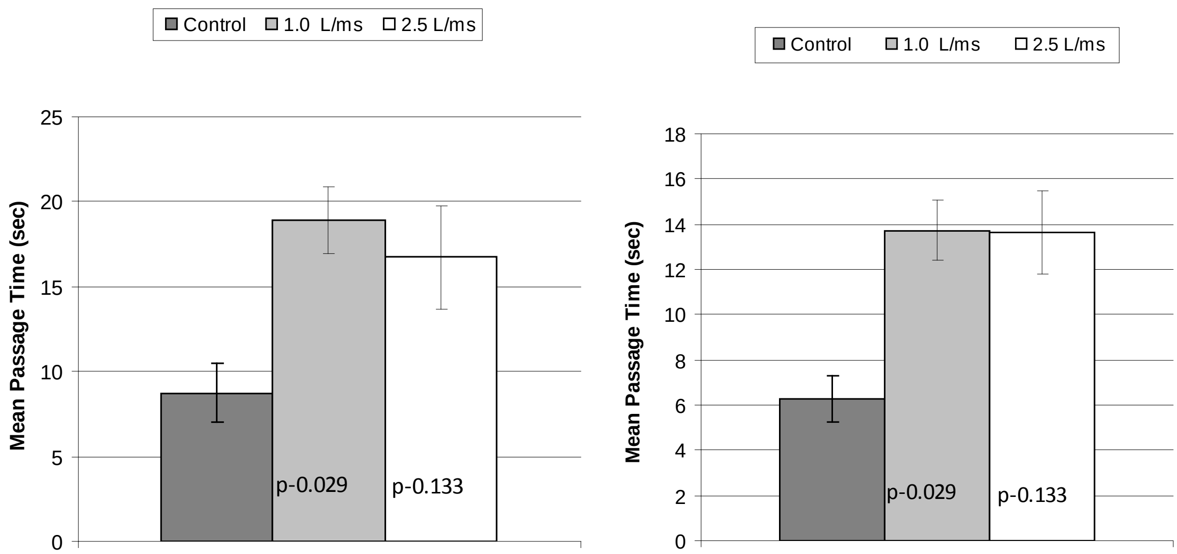



Figure 3. Mean passage time to cross Mark I barrier in the up-stream (left) and down-stream (right) direction

## 3.2 Mark II Barrier

The Mark II barrier discharges 10 times the air-supply as the Mark I barrier and represents a significantly more vigorous bubble curtain. A four antenna experimental configuration provides more information on the carp movements, as the antenna located directly over the barrier can detect the total time the carp spend near the barrier. A total of 8 tests were performed with 31.5 $Ls^{-1}m^{-1}$ air-flowrate and without air-supplied to the barrier. Figure 4 provide the total up- and down-stream passages over the Mark II barrier during the control and barrier tests. Note the decrease in passages is statistically significant, indicating that the barrier does limit carp movement.

Figure 5 displays the total number of passages between any two antennas as an indication of the relative activity of the carp being tested. Note the 30% decrease in total passages when the barrier is on is mildly statistically significant with $p$~0.05. The number of passages can be interpreted of a rate of movement by the carp over the testing period. During the control tests, the carp averaged 2 passages per minute, while that number decreased to 1.5 passages per minute. The reduced number of passages between any two antennas could be a result of the reduction of passages over the barrier, which accounts for approximately 200 passages. Despite the reduced activity between control and barrier test, it is important to note the carp are consistently active in all tests.

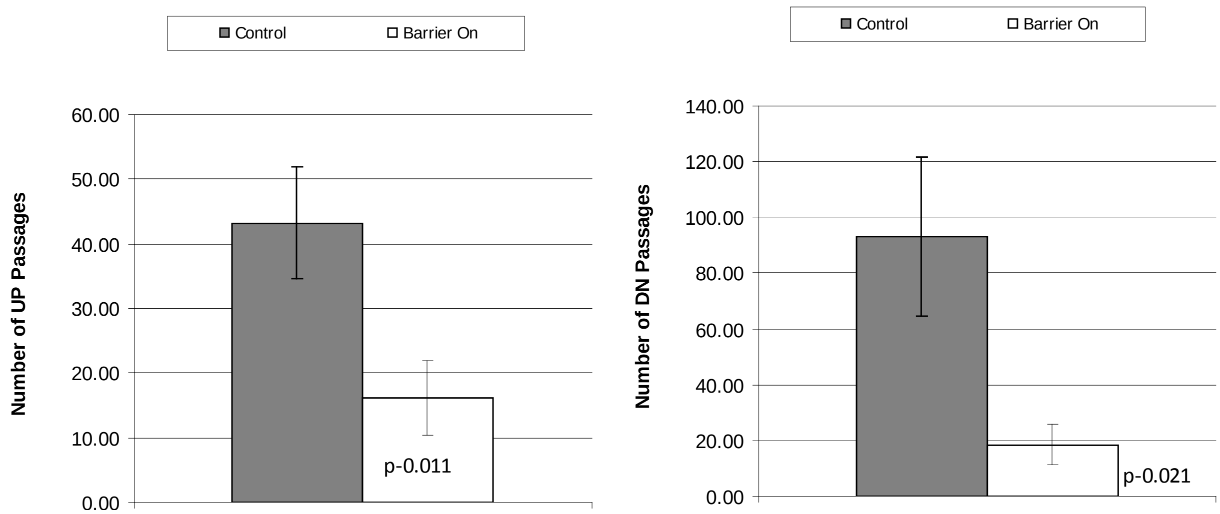



Figure 4. Total number of up-stream (left) and down-stream (right) passages over Mark II barrier

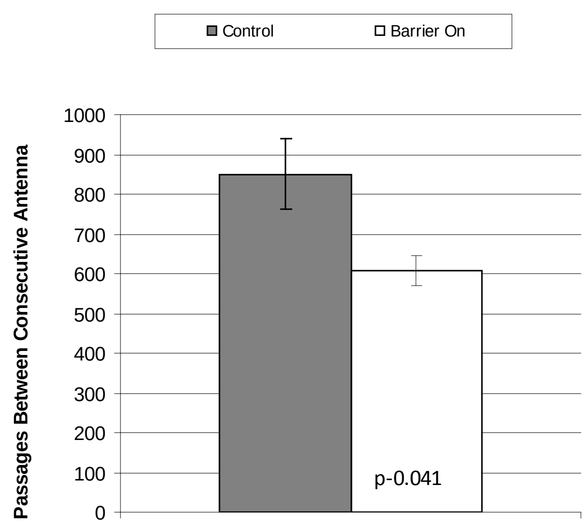


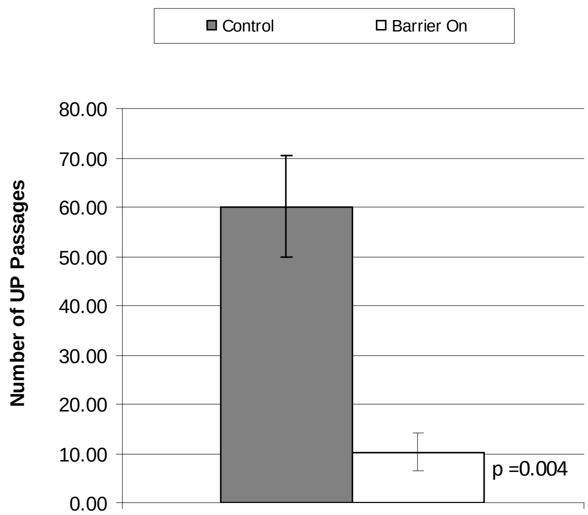

Figure 5. Total number of passages between any two consecutive antennas

Figures 4 clearly demonstrates the desired effect of the barrier on carp movment. Although the Mark II barrier does not completely stop all carp passage, it does decrease the number of passages in the up- and down-stream directions by approximately 60% and 80%, respectively. There was no statiscial difference between control and barrier tests in the passage time; however, this cannot be compared to the Mark I test results as the antenna configuration changed from 3 to 4 antennas.

### 3.3 Mark III Barrier

The Mark III barrier consists of a grid configuration of ultra-coarse diffusers supplied with an air flow rate of 108 Ls-1m-1. A total of 7 tests were performed with 108 $Ls^{-1}m^{-1}$

air flow rate and without air-supplied to the barrier. Figure 6 provides the total up- and down-stream passages over the Mark III barrier during the control and barrier tests. Note that during the Mark III barrier testing, one test resulted in zero passages during the 7 hour test period. Figure 7 displays the total number of passages between any two antennas as an indication of the relative activity of the carp being tested. Using this metric, the carp clearly maintained a similar level of activity during the control and barrier-on tests.



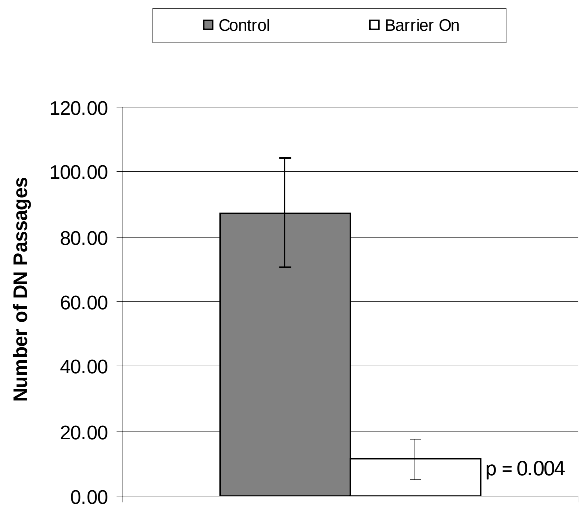




Figure 6. Total number of up-stream (left) and down-stream (right) passages over Mark III barrier

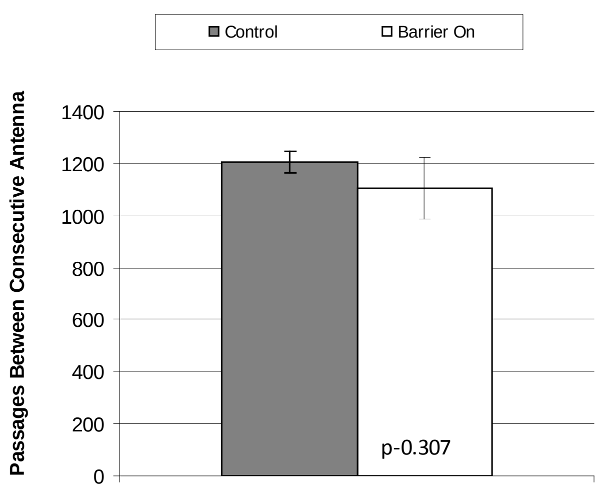



Figure 7. Total number of passages between any two consecutive antennas

Although the raw numbers are improved a rigorous analysis shows that there is no statistical difference from the Mark II barrier, resulting in a total of 75% reduction of passages in each direction.

### 3.4 Bubble Curtain Conclusions

Overall, the results of the Mark I and II barriers clearly demonstrates the accuracy and effectiveness of the RFID PIT tag detection system. The experimental configuration and testing protocal proved to be an effective method for the initial testing of the bubble barrier designs. The Mark I barrier results indicate that a 10 second delay on the carp passage over the barrier is achieved; however, no significant stoppage was observed. The Mark II barrier results demonstrated approximately a 60% and 80% decrease in carp passages in the up- and down-stream directions, respectively. With a slight decrease in carp activity between the control and barrier tests, we can show that the carp remained consistantly active during all tests.

The results of the Mark III barrier suggest that with bubbles alone we may have reached its maximum stopping potential. In this case, stopping potential is defined as the ability of a barrier to reduce the number of passages over the barrier within the testing period. In our test facility the juvenile carp are forced to stay within a close proximity of the barrier, potentially forcing more interaction with the barrier than in a natural setting. Therefore, in a natural setting when carp are not required to stay close to the barrier, the reduced number of passages could correlate to a complete stoppage of passage, hence stopping potential. With reference to the increase in air to the Mark III barrier and subsequent results indicate a further increase in the intensity of the bubbles may not lead to an increase in the effectiveness of the barrier. Although a bubble alone barrier could be a useful component in an integrated management strategy for controlling the movement and recruitment of juvenile carp, it would not be 100% effective at stopping carp movement in a given reach.

## 4.0 Macro-behavior Study

An objective of this study is to develop an understanding of carp behavior in the vicinity of a bubble barrier. In this last reporting period an analysis of the bubble barrier tests has indicated a significant change in the macro-behavior of the fish related to their swimming patterns.

The behavior pattern we are interested in observing in this analysis is the spatial variance over time, which describes how carp disperse with and without the barrier. The first step to obtaining the spatial variance, square deviation from the mean, of the carp movement data requires that a position time series be generated for each trial. The PIT tag system only records the position of the fish as it enters the reading range of one antenna, not the exact location at a set time interval. The data log must be transformed from a circular reference to linear reference to visualize the net movement during each trial. Whereas the barrier effectiveness tests only reported the crossings over the barrier in a certain direction, the position time-series will provide the net direction of movement. This is accomplished by assigning each passage between antennas with the centerline distance between antennas. Figure 8 and 9 provide the control and diffuser on test position time series data for the Mark II barrier. Note that a positive distance is in the downstream direction.

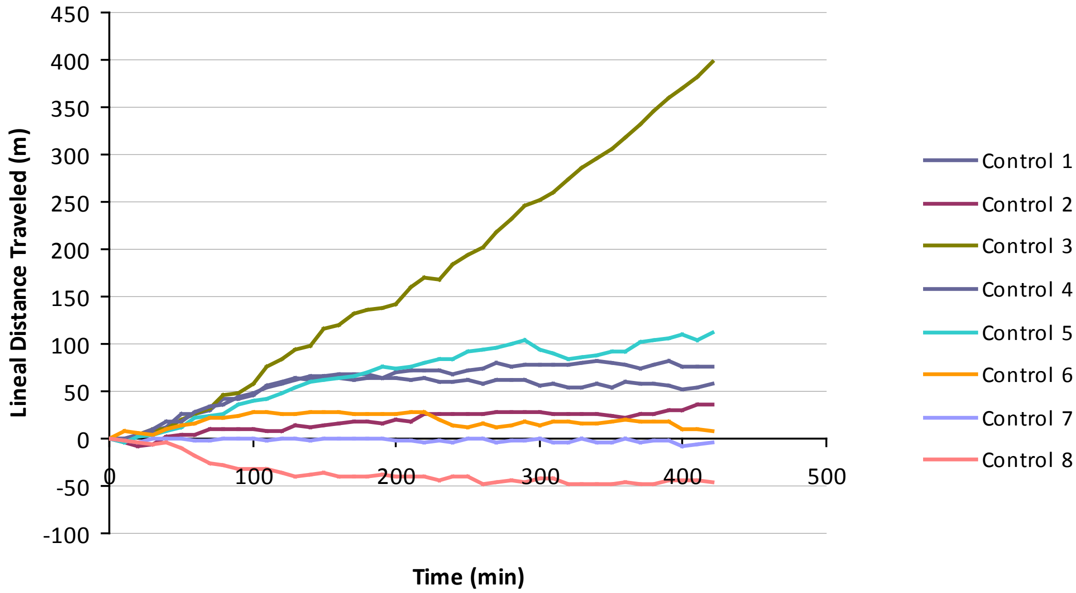



Figure 8. Position time series for Mark II control tests

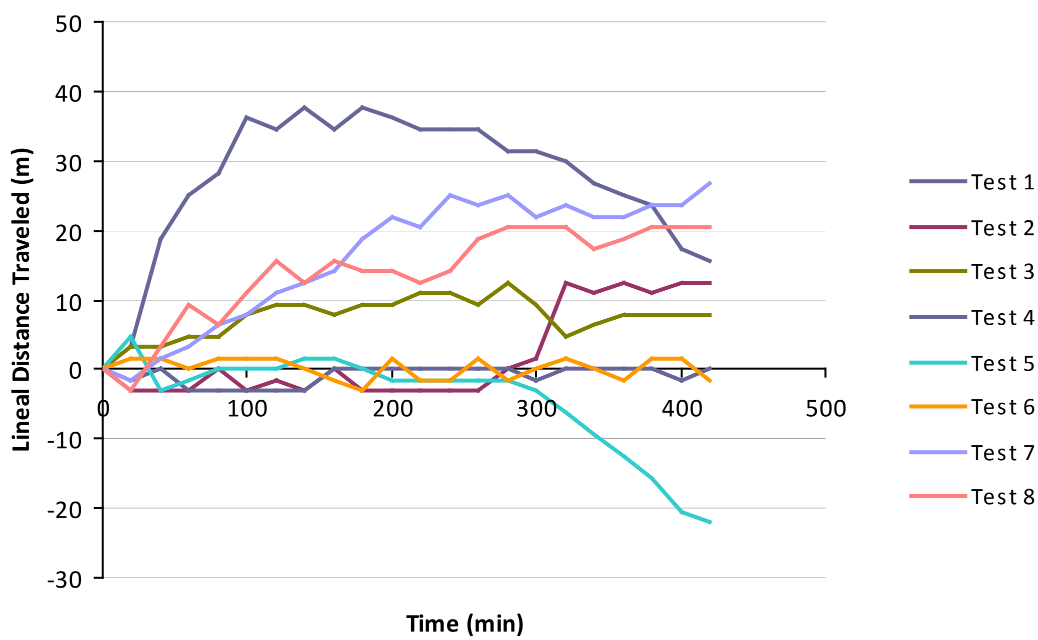



Figure 9. Position time-series for Mark II diffuser on tests

The position time-series for all trails are compiled, for the Mark II and III barrier tests, to generate the spatial variance of the carp at a specified time step of 20 mins. Each test represents the movements of one individual carp, apart from some population. Therefore, the spatial variance is a result of dispersion as opposed to pure diffusion. The low carp population during the testing may cause advective transport to dominate. Figure 10 displays the spatial variance of the control tests for the Mark II and Mark III barrier tests combined.

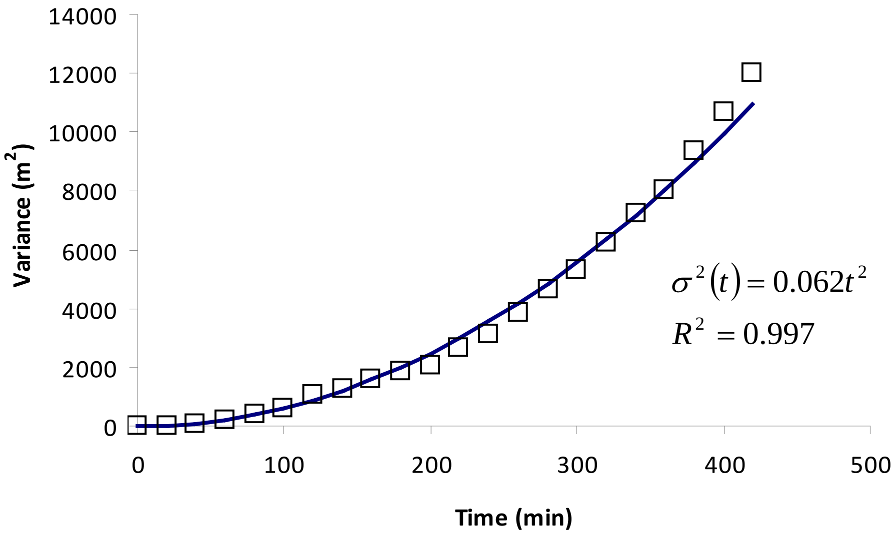



Figure 10. Dispersion of carp during control tests from Mark II and III trials combined

Note the high correlation with the power-law trend provided by the blue line in Figure 10. This relationship as well as the downstream trend in the time-series plots indicates that the carp were influenced by the slight background flow (drift) in the testing tank. Figure 11 displays the dispersion of carp during the Mark II and Mark III diffuser on trials, separately. Note that the variance of the diffuser on trials results in no discernible trend.

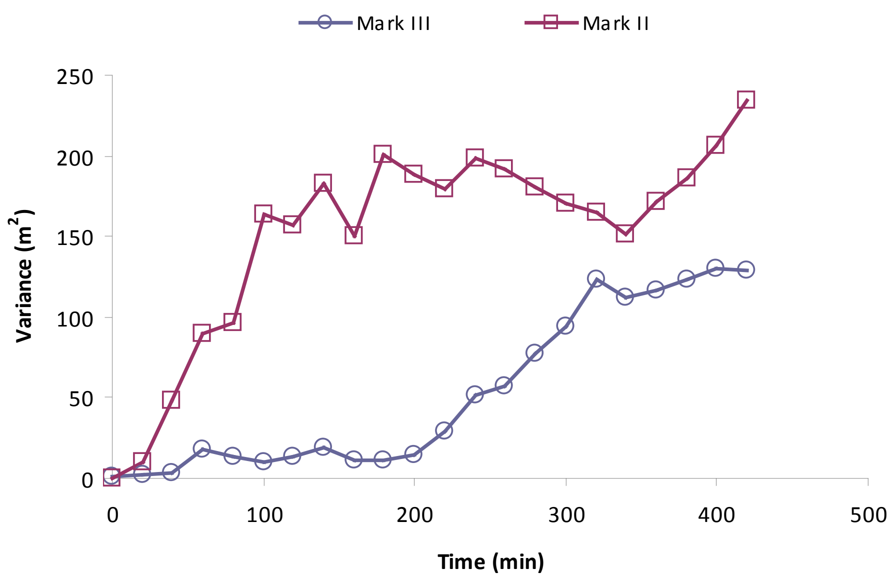



Figure 11. Dispersion of carp during Mark II and Mark III diffuser on trials

So the main conclusion to draw from this is that in the absence of the bubble barrier the average movement (drift) of the fish is clearly correlated to the presence of the small current. With the barrier operating, however, this behavior is clearly compromised and no distinctive direction of motion is observed. A breakdown of the spatial variance trend between the control and diffuser on tests indicates that a distinct behavioral change occurs. Change in carp behavior, whether it is from an avoidance response or stress, indicates that the Mark II and Mark III barriers each provide significant stimuli that carp detect and respond to.

### 4.1 Carp Behavioral Model

The objective of this phase is to develop a numerical model to describe common carp dispersal in the presence of a behavioral barrier, i.e. bubble curtain barrier. By highlighting the carp's sensitivity to sound, we have amended the classical advection-diffusion equation describing fish dispersal to account for phonotaxis (movement correlated to sound detection). Once paired with the governing equation for sound propagation in shallow water, a linear stability analysis is performed to gain some insight into how certain conditions (i.e. SPL, attenuation rate, number of carp, etc.) may result in a disruption of the downstream dispersal of carp. The results of this exercise are summarized in a manuscript for submission to *Ecological Modeling*.

## 5.0 Speaker-only Barrier

The objective of this phase is to test the effectiveness of an acoustic-only barrier. The speaker barrier provides a strong acoustic field similar to the Mark III barrier, with characteristics outlined **Result 1**, while not providing strong tactile stimulus associated with bubble curtains. Some tactile stimuli is still expected from the speaker barrier due to near field particle motion associated with sound pressure waves; however, the particle motion is considered minimal as the magnitude of motion is significantly less than that generated by turbulence caused by the bubble curtain.

### 5.1 Speaker and Speaker + Bubble Barrier Behavioral Trials

The purpose of these tests were to 1) attempt to investigate the role of sound on carp movement and 2) examine the impact of bubble curtains on speaker generated sound and how might they be paired to improve barrier performance. We did this by first mapping the acoustic field of the speaker and speaker-bubble barrier within the laboratory tank. Next, we compare the results with the acoustic field generated by the Mark III barrier. Finally, behavioral trials were completed for each new barrier and the results were compared to the bubble curtain barriers.

The behavioral trials of the speaker consisted of using the same circular tank, PIT tag system, and common carp used in previous trials. Instead of bubble diffusers, three underwater speakers were placed along the bottom of the tank. The speakers were used to approximately match the 127dB (ref 1µPa) generated by the Mark III barrier across the entire width of the test channel (Figure 12). This is consistent with the position used in **Result 1**. For the speaker-bubble barrier, fine bubble diffusers (matching Mark I, as reported in **Result 1**) were placed on either side of the speakers. The same sound sample was used in the speakers, generating the same sound amplitude, but slightly altered sound field (Figure 12). Although the sound amplitude was matched, Figure 1 shows a narrower acoustic field for the speaker and speaker-bubble barrier when compared to the Mark III barrier.

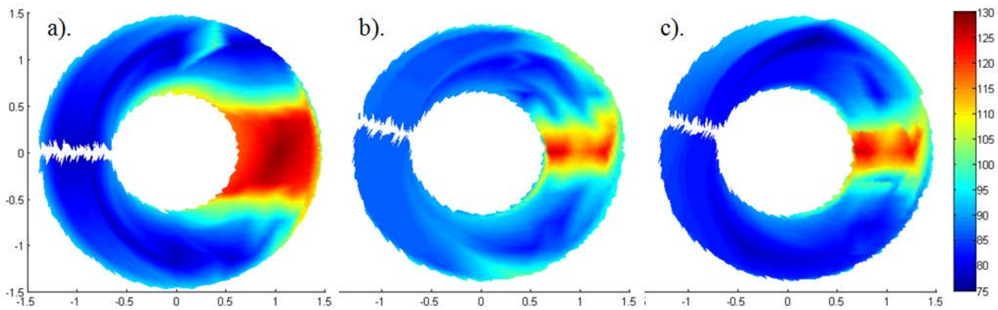



Figure 12. 2-D mapping of sound pressure level generated by a). bubble curtain, b). speaker-only, and c). speaker-bubble barrier. The origin of the x-axis and y-axis (m) is located at the center of the laboratory tank, and contours are given in sound pressure level (dB ref 1 □Pa).

Consistent with that observed in **Result 1**, sound mapping revealed the bubble curtain causes an anisotropic sound field (i.e. sound travels more efficiently in the bubbles than in water alone). The sound pressure gradient is re-oriented, with the bubble curtain creating a wall of sound. This differs from the radial attenuation of sound from the speaker alone (Figure 13).

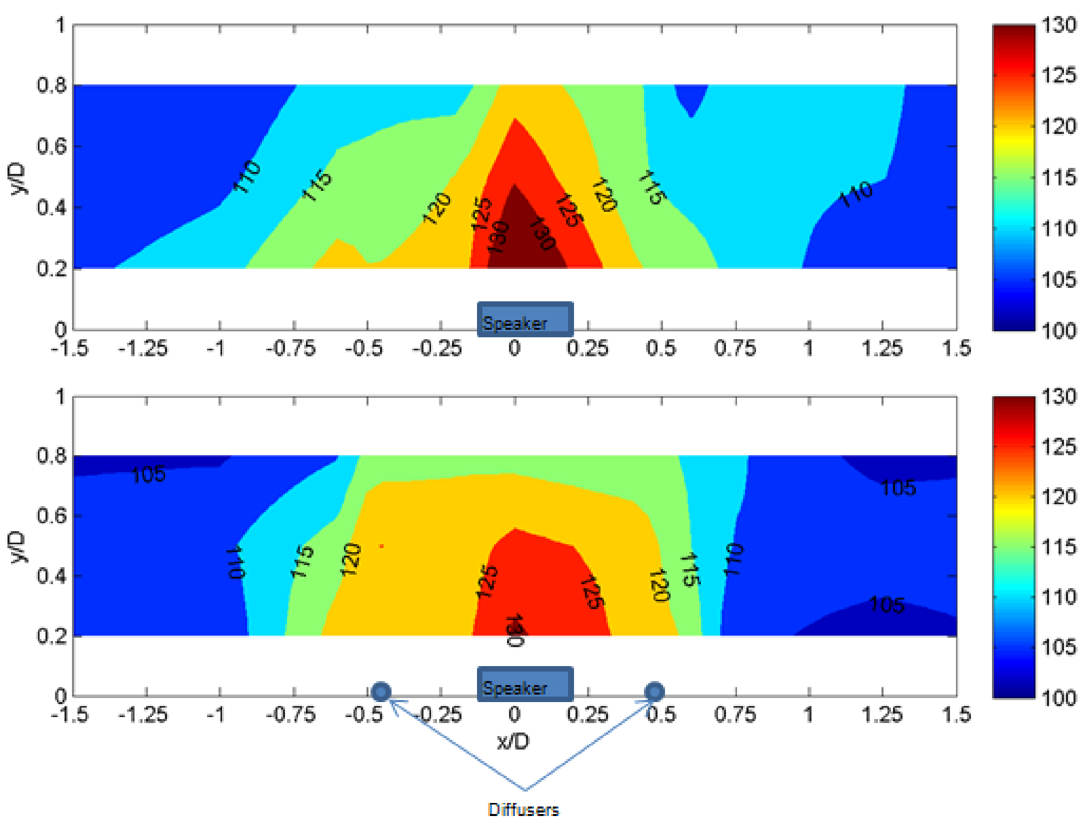



Figure 13. Sound pressure level contours through the centerline of the laboratory tank generated by the speaker (top) and speaker-bubble barrier (bottom). The contours are given in sound pressure level (dB ref 1$\mu$Pa).

The behavioral trials for the speaker and speaker-bubble barrier used a sample size of N=7, matching the Mark III trials; therefore, the efficacy of the barriers was determined by comparing the passage of carp over the barrier to the previous controls. Figure 14 provides the number of up-and down-stream passages over the barrier made by carp for the speaker, speaker-bubble, and Mark III barriers. Note that the decrease in passage during the speaker tests were not statistically significant (P>0.05), indicating that sound amplitude alone has minimal impact on carp. In contrast, the speaker-bubble barrier inhibited carp passage similar to the Mark II and III barriers, ~75%. In this case, the bubbles alone generated only ~90 dB (ref 1mPa), and was unable to limit carp movement (see Mark 1 barrier results). This suggests that the sound characteristics of bubble plumes (i.e. sound anisotropy, pressure gradient orientation, etc.) may play an important role in controlling carp movement. Therefore, underwater speakers could be paired with the Mark II or Mark III barrier to potentially improve barrier efficacy.

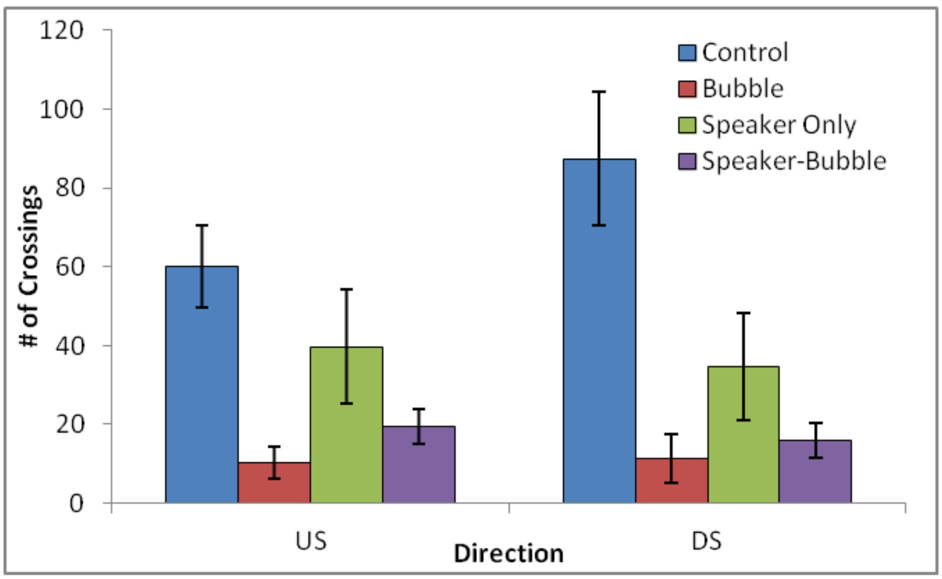



Figure 14. Total number of passages in the up- and down-stream direction (+/- Standard Error) during control and barrier-on trials. The * denotes a p<0.05 using a non-parametric Mann-Whitney U-Test.

### 5.2 Additional sound and bubble behavioral testing

The objectives of this phase where to 1) further investigate sound propagation through a bubble curtain and 2) identify ways to improve the Kohlman Creek barrier with an underwater speaker. Using the speaker/bubble curtain system, we played back randomized pure tone signals in the speaker system. The pure tone signals were selected from the most sensitive carp hearing range (250-1500 Hz). Pure tone signals were also chosen to simplify the sound propagation dynamics through the bubbly media. Sound pressure maps near the barrier system were obtained for signals at 250, 500, 1000, and 1500 Hz. Preliminary data shows that the sound pressure field is anisotropic across the bubble curtains. At all frequencies, the sound pressure level peaked right above the speakers and decreased rapidly through the bubble curtain; however, at higher frequencies (those at or above the shallow water cutoff frequency of

1000Hz) the anisotropic field diminishes closer to the water surface.  Data from subsequent behavioral trials using the speaker/bubble curtain suggests that carp deterrence was not increased by the random signal.  Carp may not have avoided the system because of acclimation to a slowly changing pure tone signal (with randomly changing signals lasting 5-8 sec.

Additional testing was performed using the same set-up, but the sound signal consisted of three random generated pure-tone frequencies (each tone lasting less than 1 sec) between 100 and 2000 Hz.  Spectral analysis showed that this signal produced a more broad-spectrum sound than the pure tone signal (i.e. acoustic energy is spread over a wide range of frequencies).  The sound pressure level was observed to decrease rapidly through the bubble curtains.  Data from behavioral trials again revealed no significant increase in deterrence over the bubbles-only.  Despite the lack of success of two simplistic engineered signal trials, we know that a replay of the bubble curtain sound was just as effective at deterring carp as the real thing.  Thus, engineered signals may still improve barrier efficacy, but further research is needed to identify specific signal characteristics that garner stronger responses from carp.

**Result 3:** Field channel investigation

**Description:** The objective of this phase is to integrate the engineering and biological studies in results 1 and 2 to construct an outdoor carp barrier which employs a bubble curtain(s). This study will be conducted in the Outdoor Stream Laboratory Stream Lab (OSL and, in cooperation with Ramsey Watershed, Kohlman Creek near Maplewood. The main goal is to test the effectiveness of bubble curtain barriers in stream conditions.
.

**Summary Budget Information for Result 3:** **Trust Fund Budget: $ 98,862**
**Amount Spent: $ 91,589**
**Balance: $ 7,273**

| **Deliverable** | **Completion Date** | **Budget** |
|---|---|---|
| **1.** Testing and documentation of the effectiveness of bubble curtain barriers to deter the movement of carp in small streams (SAFL OSL and Kohlman Creek) | 6/30/2011 | $32,044 |
| ***2.*** Identification of the bubble diffuser designs that have the best potential to create bubble curtain based carp barriers for small streams.  (SAFL OSL, Kohlman Creek, and main channel) | 6/30/2013 | $66,818 |

**Completion Date:** 6/30/2013

**Final Results Summary**

## 1.0 Introduction

A prototype bubble barrier was installed in the Outdoor Stream Lab (OSL) at the Saint Anthony Falls Laboratory in July 2011 and a field scale bubble curtain was installed in Kohlman Creek, Maplewood, MN, in July 2012. The OSL prototype test had two objectives (1) determine if the barriers developed for the laboratory tests can be successfully implemented in a field setting, and (2) determine if natural conditions effect the “stopping potential” of the bubble barrier. The Kohlman Creek barrier had the dual purpose of 1) validating the laboratory results of **Result 2** under natural conditions, and 2) assess the potential of the bubble curtain to be used as a management tool for common carp. The following sections outline the design, installation, and testing of the bubble barrier within the OSL and Kohlman Creek

## 2.0 OSL Prototype Design

The prototype bubble barrier design was based on the Mark II barrier, for the simplistic layout. A rigid platform was constructed of 1/2in thick plexi-glass to prevent scour and immobilize the diffusers. The barrier was placed within a channel section with dimensions of 1.5m wide and 30cm deep. Gaps around the bubble barrier platform were blocked with plastic mesh anchored into the substrate. Figure 1 displays the initial placement of the barrier within the OSL. A rock vane located 4m upstream of the barrier created a scour hole immediately downstream that increased the depth and decreased the stream velocity near the barrier.

Figure 1. Placement of prototype barrier within the OSL

Air was supplied to the barrier with two Sweetwater S41 regenerative blowers in parallel providing 31.5 $Ls^{-1}m^{-1}$ air-flowrate. Fish movement was monitored by the same PIT tag system utilized in the laboratory trials. Due to antenna interference, the PIT antennae were placed on the bottom of the channel as seen in Figure 1 (yellow wires). The usable channel length by carp was limited to 2m upstream and 5m downstream of the barrier with weighted nets spanning the channel width. Figure 2 displays the net upstream of the barrier and upstream rock vane.

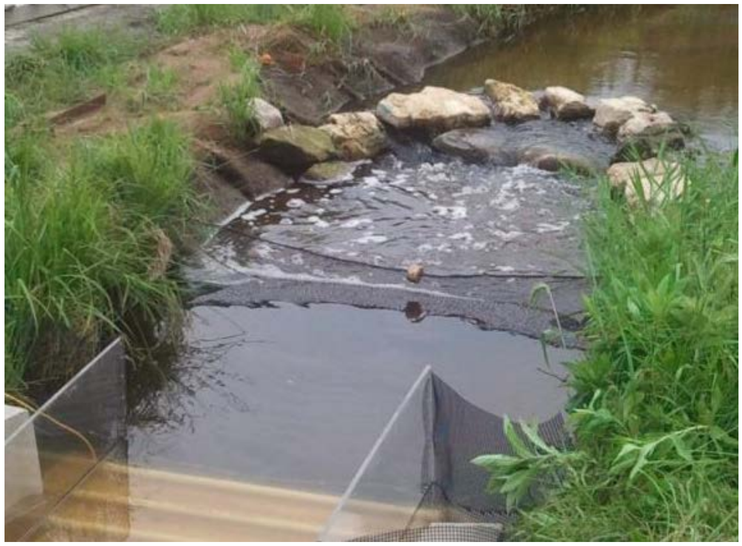


Figure 2.  Netting and rock vane located upstream of barrier

The overall location of the barrier with nets is provided in Figure 3.  Note the relatively consistent channel width throughout the test section.

Figure 3.  Aerial view of OSL bubble barrier test section

## 2.1 Behavioral Trials in OSL

Behavioral trials were performed in the OSL similar to the laboratory trials in **Result 2.** Each trial consisted of placing three carp (two untagged, one tagged) into the stream, upstream of the barrier.  The carp were allowed to acclimate for 10min prior to recording data and each trial lasted 7hrs, starting at 10:00PM.  Initial plans were to perform 3 control trials and 3 barrier-on trials.  Unfortunately, data recording and fish enclosure issues decreased the number of trials completed.  During the summer months, the OSL is used for a large number of studies, limiting the amount of time available for the behavioral trials.  The short time window for testing in the OSL in July prevented any adjustments from being made, so no behavioral information was collected.

This initial trial did at least prove that the field prototype barrier can be successfully implemented in a real stream channel. Acoustic measurements confirmed the SPL of 100dB (ref 1µPa) on the upstream edge and 130dB (ref 1µPa) on the downstream edge, consisted with the Mark II barrier. The bubble curtain was consistent across the entire width of the channel, while bypass was adequately prevented with the plastic mesh.

Overall, the first objective of the OSL trials was met, but the second was not achieved due to poor experimental controls. Therefore, in late October, when the OSL became available for further testing, we attempted to replicate the earlier tests. As the OSL channel morphology had changed due to differing experiments run since July 2011, we had to move the barrier location further downstream. We placed the approximately 1m downstream of a static riffle section. The section of channel used for the behavioral test was approximately 6m long x 1m wide x 0.25m deep (average). The barrier was placed at the deepest section, which left only 1m upstream and 4m downstream for the carp to avoid the barrier. Again, we had a limited window of opportunity to perform the behavioral trials. This time the water temperature was nearing 10° C, which is approximately the minimum threshold for common carp to continue foraging for food (i.e. below this, the carp may tend to move significantly less as they severely limit their food intake due to bioenergetic restrictions). Due to this limitation, we revised our testing procedure to include two 48-hr long trials.

Each trial consisted of placing three carp (two untagged, one tagged) in the channel for 24-hrs without the air supplied to the barrier. The following 24-hr period used the same fish, but air was now supplied to the barrier. The difference between the number of crossings with and without air supplied to the barrier was recorded and used as an approximate estimation of the barrier's efficacy. Between the two trials (six fish total), the reduction in the number of crossings was 55%. This value was much lower than observed in the laboratory trials, but still indicated a similar behavioral change. One reason for the lowered efficacy was due to the limited space for carp to avoid the barrier (only 1m of stream was available upstream of the barrier).

## 3.0 Kohlman Creek Bubble Curtain Barrier

In cooperation with the Ramsey-Washington Metro Watershed District, we constructed and installed a prototype bubble curtain barrier to investigate the potential to inhibit common carp movement in a natural stream. The barrier is located in Kohlman Creek, immediately upstream of Lake Kohlman near the intersection of HWY 61 and Beam Ave in Maplewood, MN. Figure 4 provides a basic site plan of the barrier site. Temporary dock structures were designed and installed by Barr Engineering in May 2012. These docks were used to secure the bubble diffusers to the bottom of the stream and provide access to the barrier and fish traps (Figure 5). The bubble curtain is designed after the Mark II barrier and is supplied air by two regenerative blowers housed on the shore. Movement of carp within the stream is monitored by a PIT tag interrogation system. Similar to the laboratory system, PIT tag implanted carp are placed upstream of the barrier and their movement (or lack thereof) across the barrier is captured by two PIT antennas located immediately downstream of the barrier (Figure 6). Additional PIT antennas could not be installed due to significant interference caused by nearby powerlines.

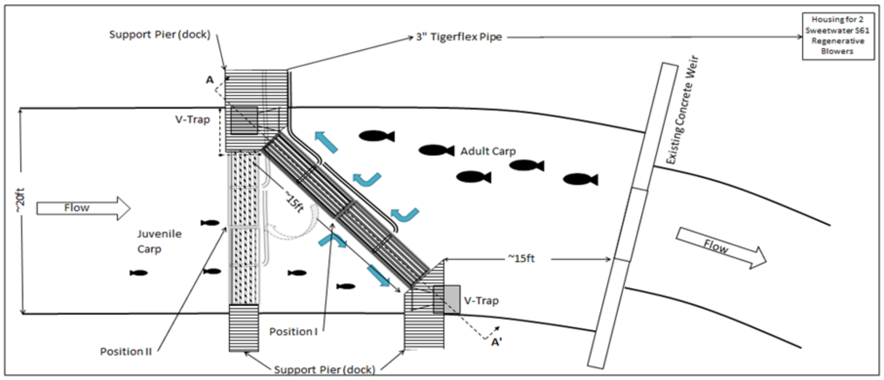



Figure 4.  Site plan of Kohlman Creek bubble barrier.  Position I and II denote the alternative orientations of the bubble diffusers.

Figure 5.  Kohlman Creek bubble barrier looking downstream.

Figure 6.  Typical PIT antenna located approximately 10m downstream of the bubble barrier.

The goal of this project was to determine the efficacy of a bubble curtain barrier to inhibit downstream movement of juvenile carp and upstream movement of adult carp within Kohlman Creek. As a management tool, the barrier is designed this system is to 1) limit the access of adult carp to “nursery lakes” in the headwaters of the system, and 2) restrict the recruitment of juveniles out of these waters back to Lake Kohlman. The barrier was not constructed early enough this spring to be tested during the natural upstream movement of adult carp out of Lake Kohlman.

## 3.1 Behavioral Tests

### 3.1.1 Downstream Movement Tests

Downstream movement tests were conducted using carp collected from the headwater region (Markham Pond, Casey Lake, and Upper Basin) that we assumed would try to move downstream into the main lakes. Common carp were caught by electrofishing and released into Kohlman Creek near the bubble curtain for testing. All captured fish were measured for length (mm), surgically implanted with a 23 mm PIT tag, and released ~5 m above or below the bubble curtain.

For downstream movement tests, $P_{test}$ is the proportion of fish released above the bubble curtain that passed downstream through the bubble curtain while ON, and $P_{control}$ is the proportion of fish released below the bubble curtain that swam downstream un-impeded by the bubble curtain (Figure 7). It was assumed that, $P_{control}$ represents the expected ratio of test fish to swim downstream in the absence of a bubble curtain.

Bubble curtain operation was cycled every 24 hrs during the tests. Alternating bubble curtain operation not only allowed for evaluation of bubble curtain performance, but downstream passages while the bubble curtain was OFF provided further evidence the headwater carp were motivated to move downstream. Each test period continued until all carp move downstream, out of Kohlman creek, but no longer than 4 days (2 cycles of bubble curtain operation). The temporary fish screen was open during all downstream movement tests.

The primary metric for evaluating bubble curtain efficacy to inhibit downstream movement is the PIT tag detections at the antennas downstream of the bubble curtain. Only one antenna is required for these tests since any detection of carp released above the bubble curtain indicates a crossing. As a result, the culvert antenna was used only as a back-up to the concrete weir antenna. In order to account for potential PIT tag rejection, fatality, predation from birds, or missed antenna detection, only carp detected by the PIT antennas are used in the evaluation of bubble curtain performance.

### 3.1.2 Upstream Movement Tests

Upstream movement tests were conducted using carp collected from Kohlman Creek, immediately downstream of the temporary fish screen. Collection and testing of these fish only occurred at times when natural upstream migration occurred, thus ensuring carp were motivated to challenge the bubble curtain. Fish were trapped between the temporary fish screen and a custom net and caught by electrofishing, then transplanted further upstream in Kohlman Creek for testing. These carp were typically captured along with 20-100 additional carp trying to move upstream at the temporary screen. All carp not used for testing were euthanized and removed from the system. All fish captured for testing were measured for length (mm), implanted with a 23 mm PIT tag, marked with reflective ribbon tied to the anterior spine of the dorsal fin (control and test fish received different colors) for visual monitoring, and released ~5 m up- and down-stream of the bubble curtain (Figure 7). Based on age-length relationships, the carp used in upstream testing, larger than 550 mm TL, were age-2+. These carp were also examined to identify sex and maturational condition by gently squeezing the fish. In total, 18 males and 22 females were selected for testing the bubble curtain against upstream movement. These tests only lasted 24 hrs because all fish were observed either crossing the bubble curtain or leaving the stream entirely before 24 hrs elapsed. During testing, the bubble curtain was continuously operated.

For upstream movement tests, $P_{test}$ was the proportion of fish released below the bubble curtain that passed upstream through the bubble curtain while ON, and $P_{control}$ is the proportion of fish released above the bubble curtain and moved more than 15 m upstream un-impeded by the bubble curtain (Figure 7). Again, it was assumed that $P_{control}$ represented the expected ratio of test fish to swim upstream in the absence of a bubble curtain. During the first 6 hrs of testing, the temporary fish screen was opened, allowing carp to swim downstream and return to the main lakes. The temporary fish screen was closed overnight, however, to prevent uncontrolled release of adults into the headwater region.

Since no PIT antennas could be installed upstream of the bubble curtain, we had to rely on visual monitoring to track carp movement. The locations of marked carp were visually monitored by an observer that walked the entire length of Kohlman Creek (~130 m) twice every 3 hrs after the start of each test, during daylight hours. In addition to visual monitoring, any downstream movement (i.e. carp returning to the main lakes) was monitored by the PIT antennas. In the event of lost ribbon or PIT tag loss/fatality, only fish observed in the stream or detected by the PIT antennas was included in the evaluation of the bubble curtain performance.

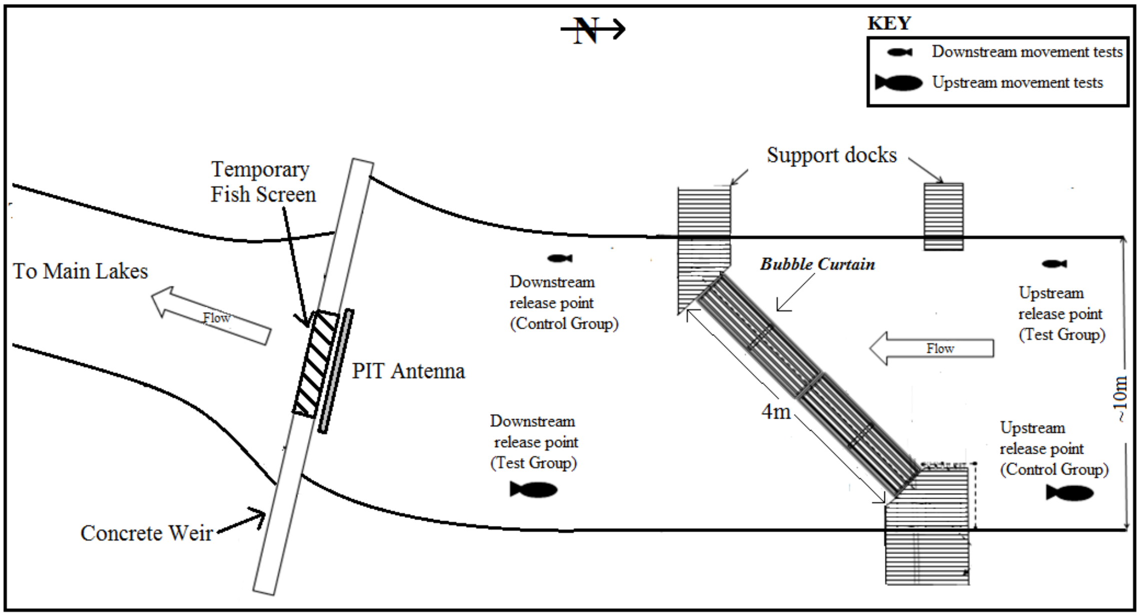



Figure 7. Plan view schematic of the bubble curtain system in Kohlman Creek with locations of release points for each movement test.

### 3.1.3 Results

During tests in 2012 and 2013, 84% (51 of 61) of PIT tagged carp were detected during the downstream movement tests. In total, 17 of 51 ($P_{test} = 0.33$) carp from the test group (placed above the bubble curtain) swam downstream through the bubble curtain while ON. In contrast, 20 of 25 ($P_{control} = 0.77$) carp from the control group (placed below the bubble curtain) swam downstream into the main lakes. The efficacy (percentage decrease in expected passage) of the bubble curtain to block downstream movement of common carp in Kohlman Creek is 57±12% (±SE) (Chi-squared test, P<0.001). Efficacy of the bubble curtain was consistent across each test period (Mantel-Haenzel Chi-squared, $\chi^2_{assoc} = 10.6$, P<0.001).

Carp from the control and test groups typically did not pass downstream until after dark (Figure 8); however, one test carp did cross the bubble curtain within two hours of the test start (~1400 hrs). Within the first 24 hrs, 57% (n=15) of the control group carp swam downstream, while only 25% (n=13) of the test group swam downstream through the bubble curtain.

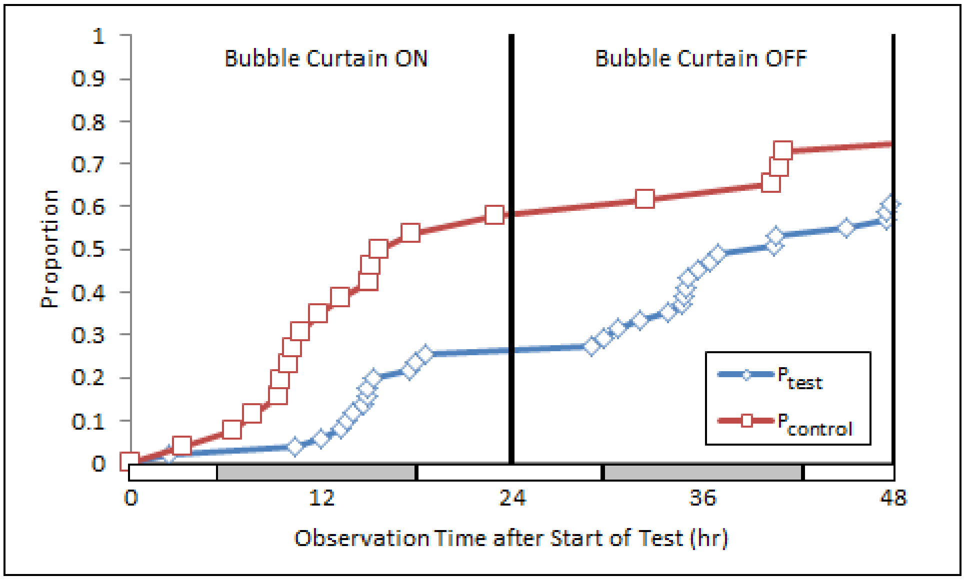



Figure 8. Proportion of test and control carp that swam downstream over one cycle of bubble curtain operation. The start time for the downstream movement tests was approximately 14:00 hr. Dark and light bars at the bottom indicated night and day.

Between all upstream movement tests 5 of 40 carp lost their reflective ribbons, and were removed from the data set. Additionally, the test on 05/19/2013 was terminated after 4 hrs due to severe flooding in Kohlman Creek that prevented visual observations. In total, 14 of 23 ($P_{test} = 0.74$) carp from the test group (placed below the bubble curtain) swam upstream through the bubble curtain while ON. Similarly, 7 of 8 ($P_{control} = 0.88$) carp from the control group (placed above the bubble curtain) swam upstream towards the headwater region. The control carp were generally observed in small tributaries approximately 50 to 75 m upstream of the release point. Bubble curtain efficacy for blocking upstream movement of carp is 16±11% (Chi-squared test, $P > 0.05$). The significance of association test was not preformed because upstream tests did not reveal any significant level of blockage over 24 hrs. Although the bubble curtain was unable to ultimately block upstream movement of common carp, the bubble curtain did delay more than 50% of adult carp upstream passage by 6 hrs (Figure 8).

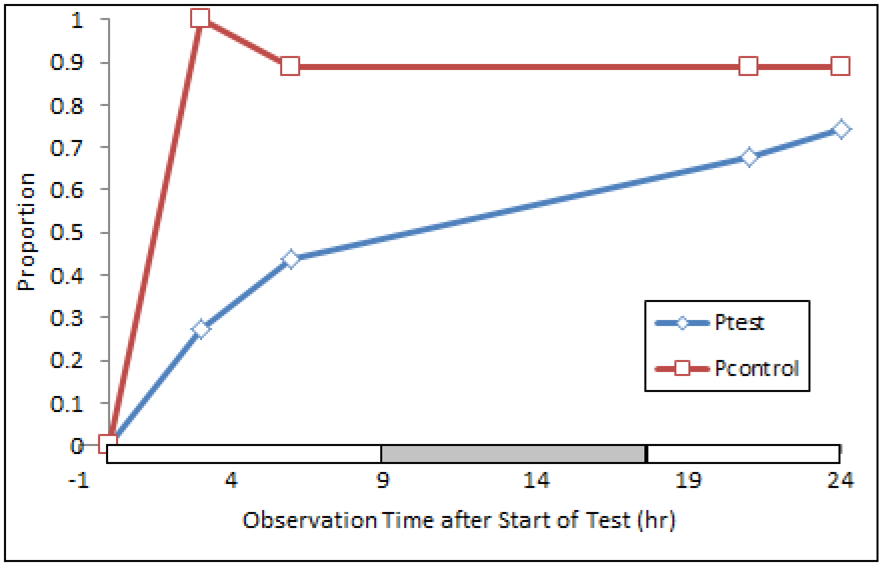



Figure 8. Proportion fish from test and control groups to swim upstream towards the headwaters region over the 24hr test period. The bubble curtain was ON throughout each test. The start time for the upstream movement tests was approximately 12:00 hr. Dark and light bars at the bottom indicated night and day.

### 3.2 Conclusions

This study found a bubble curtain reduced downstream movement of common carp in the field by 57±12%. Although our finding was less than the 75-80% efficacy reported from the laboratory trials, overall performance of the bubble curtain in the field was consistent with laboratory observations. In contrast, results of upstream movement tests revealed that the bubble curtain had negligible impact (efficacy < 20%) on stopping upstream migrating carp. In fact, the bubble curtain only delayed upstream passage by 6hrs for half the test carp. These results suggest the bubble curtain is not effective against highly motivated carp, like those migrating upstream for spawning. In general, carp placed above the bubble curtain (control group) were observed far upstream (> 100 m), near the sheet pile weir, within 1-2 hrs after the test started; while carp placed below the bubble curtain (test group) remained downstream or returned to the main lakes. Although the reported efficacy may be insufficient for management efforts now, simple modifications like repositioning or additional deterrent stimuli to improve efficacy by 10-15% may make bubble curtains a realistic management tool for sites where reduction, not total elimination, of movement is the goal.

## V. TOTAL TRUST FUND PROJECT BUDGET:

**Personnel**: $262,563

**Equipment/Tools/Supplies**: $31,837

Details of estimated expenditures

--Modifications of Flumes (2-3 small laboratory flumes) (includes, refurbishing, plumbing and pumps, sound installation, instrumentation); $10,732

--Modification of SAFL Outdoor Stream Lab and Main channel (includes, hardware for channel design, Instrumentation for monitoring environmental conditions -water quality, temperature, flow-, compressors for bubble generation); $2,000 (an amount reflecting costs incurred in initial SAFL site tests

---Manufacture of diffusers to create bubble curtains in laboratory and field conditions $5,500

~~--4~~ Hydrophone and recorder plus cables, batteries, memory cards (to measure and create sound, B&K 8103 or similar, $1000 per). Whole system approximately $3,600

--PID Tag system, antenna wire, antenna packs to detect fish at filed barrier site, approximately $2,700

--PIT reader, tags ~$3,300

--2 regenerative blowers ($762/ea) ~$1,600

--2 speakers Lubell Labs ($900/ea) ~$1,800

--radio tags ~$3,300

--Video Camcorder with DVD recording and infrared capabilities ~$900

--Lap-top computer with lab-view software dedicated to data collection and signal processing from hydrophones $1,200

--Cost of fish (~1500 juvenile carp with fed-ex shipping and handling, $3 per fish) $4500

--Fish Storage Tank, $1,500

--Fish Care and feeding, $4,000

--General experimental supplies (tubing, data storage devices, clamps, etc). $2,700

**Travel:** $1,600

($ 500 will go towards travel to in-state meetings and $1,100 will be used to rent transport resources to deploy heavy equipment at the filed site.)

**TOTAL TRUST FUND PROJECT BUDGET: $300,000**

**Explanation of Capital Expenditures Greater Than $3,500:**

## VI. PROJECT STRATEGY:

### A. Project Partners:

Vaughan Voller, Civil Engineering and SAFL (PI)  $16,500
Miki Hondzo, Civil Engineering and SAFL (Co-PI) $15,000
Allen Mensinger, Biology, UMD (Co PI), $16,000
Peter Sorensen, Fisheries, Wildlife and Conservation Biology (Co-PI) $15,000
Jon Christian Svendsen (Post-Doc Nov 2010 thru Aug 2011 ) $33,465
Mike Plante SAFL (Machinist) $3000
G Dan Zielinski( Graduate Student) $154,598
TBA Undergraduate RA $9,000

**B. Project Impact and Long-term Strategy:**
Common carp (*Cyprinus carpio*) comprises over half the biomass in a third of Minnesota lakes. The feeding habits of this species significantly disrupt lake sediments leading to an over-enrichment of nutrients. This process, referred to as eutrophication dramatically reduces water quality. Research on the common carp is actively supported by the LCCMR and two watershed districts and is demonstrating that the root of the problem are common carp 'nursery' lakes which feed into larger lakes through small creeks. However, while presently funded/ ongoing research is suggesting solutions to suppress carp reproduction and abundance in these nurseries, the utility of this work could be held back by an inability to stop young carp from re-infesting cleared systems through the inter-connected creeks. Fish barrier technologies that show promise for this application are those based around air bubble curtains. Not only do the physical fields, e.g., sound and displacement, generated by bubble curtains have the potential to be targeted to exploit the biology of carp, barriers based on bubble curtains can also be inexpensive, portable, and safe. To date, however, there has been no public domain research on appropriate design guidelines for optimizing air bubble curtain barrier technologies. The main objective of this proposal is to address this shortfall and provide design guidelines for the use of bubble curtain barriers in small inter-connecting creeks. In addition to providing a potential ecological management tool for the control of common carp already in Minnesota lakes this project may also provide key information toward building effective tools for the Asian carp; a species which poses a very similar suite of challenges.

**C. Other Funds Proposed to be spent during the Project Period:**
Salary support for the participation of the manager of the Outdoor Stream Lab at SAFL in this project will be covered by funds from SAFL. In addition basic operating costs for this major research facility will be also be covered by SAFL

**D. Spending HIstory:**

## VII. DISSEMINATION:

1. Publications in peer-reviewed literature
2. Presentations at scientific meetings
3. Web site, http://personal.ce.umn.edu/~voller/

## VIII. REPORTING REQUIREMENTS:

Periodic work program progress reports will be submitted not later than 3/31/2010(Note due to hiring logistics project will not start until Aug 30, 2009), 9/30/2010, 3/31/2011, 9/30/2011, 3/30/2012 ,1/10/2012 A final work program report and associated products will be submitted between June 30 and August 1, 2013 as requested by the LCCMR

## References Cited


Akamatsu, T., Okumura, T., Novarini, N., Yan, H.Y., (2002) Empirical refinements applicable to the recording of fish sounds in small tanks. J. Acoust. Soc. Am. 112, 3073-3082.

Brevik, I., and Ø. Kristiansen. 2002. The flow in and around air-bubble plumes. *International Journal of Multiphase Flow* 28 (4) (4): 617-34.

Chen, Huey-Long, Miki Hondzo, and A. R. Rao. 2001. Estimation of turbulent kinetic energy dissipation. *Water Resources Research* 37 (6): 1761-9.

Dawson, H.A., Reinhardt, U.G., Savino, J.F., (2006) Use of Electric or Bubble Barrier to Limit the Movement of Eurasion Ruffe (Gymnocephalus cernuus). J. Great Lakes Res. 40-49.

Fannelop, T. K., S. Hirschberg, and J. Küffer. 1991. Surface current and recirculating cells generated by bubble curtains and jets. *Journal of Fluid Mechanics* 229 (1): 629-57.

Kundu, P., (1990) Fluid mechanics. San Diego: Academic Press.

Leighton, T.G., (1994) The acoustic bubble. Academic Press, San Diego, CA. 913 pp.

Lin, J.N., Banerji, S.K., Yasuda, H., (1994) Role of interfacial tension in the formation and the detachment of air bubbles. Langmuir 10, 936-942.

Manasseh, R., Nikolovska, A., Ooi, A., Yoshida, S., (2004) Anisotropy in the sound field generated by a bubble chain. Journal of Sound and Vibration 278, 807-823.

Popper, A.N., (1972) Pure-tone auditory thresholds for carp, Cyprinis carpio. J. Acoust. Soc. Am. 52 (6): 1714-1717.

Popper, A.N., Carlson, T.J., (1998) Application of Sound and Other Stimuli to Control Fish Behavior. Transactions of the American Fisheries Society 127, 673-707.

Taylor, R.M., Pegg, M.A., Chick, J.H., (2005). Response of bighead carp to a bioacoustic behavioral fish guidance system, Fish. Manage. Ecol. 12, 283-286.

Tonolla, Diego, Mark S. Lorang, Kurt Heutschi, and Klement Tockner. 2009. A flume experiment to examine underwater sound generation by flowing water. *Aquatic Sciences - Research Across Boundaries* 71 (4): 449.

Urick, R.J., (1975) Principles of Underwater Sound, McGraw-Hill, New York, NY. 423 pp

Webb, J.F., Montgomery, J.C., Mogdans, J., (2008) Bioacoustics and the lateral line system of fishes. In: Webb, J.F., Fay, R.R., Popper, A.N. (eds) Fish bioacoustics, Springer Science+Business Media, New York, 17-48.

Welton, J.S., Beaumont, W.R.C., Clarke, R.T., (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.

Zydlewski, G. Barbin, A. Haro, and S. D. McCormick. 2005. Evidence for cumulative temperature as an initiating and terminating factor in downstream migratory behavior of atlantic salmon (salmo salar) smolts. *Canadian Journal of Fisheries and Aquatic Sciences* 62 (1): 11.

**Project Title:Novel barrier technologies for invasive species of fish**
**Project Manager Name:** *Vaughan Voller*
**Trust Fund Appropriation: $** *300,000*

| **2009 Trust Fund Budget** | **Result 1 Budget** | **Amount Spent *(6/30/13)*** | **Balance (5/20/13)** | **Result 2 Budget** | **Amount Spent (6/30/13)** | **Balance *(5/20/13)*** | **Result 3 Budget** | **Amount Spent (5/30/13)** | **Balance *(5/20/13)*** | **TOTAL BUDGET** | **TOTAL BALANCE** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Laboratory Investigation: Engineering* | | | *Laboratory Investigation: Biology* | | | *Field channel investigation.* | | | | |
| **BUDGET ITEM** | | | | | | | | | | | |
| **PERSONNEL: wages and benefits** | 85,881 | 85,881 | 0 | 98,000 | 98,000 | 0 | 78,682 | 78,682 | 0 | 262,563 | 0 |
| Vaughan Voller(PI) 4%FTE ($16,500) | | | | | | | | | | | |
| Miki Hondzo(Co-PI) 4%FTE ($15,000) | | | | | | | | | | | |
| Allen Mensinger(Co PI) 6%FTE ($16,000) | | | | | | | | | | | |
| Peter Sorensen(Co-PI) 4%FTE(15,000) | | | | | | | | | | | |
| Post_doc 100%FTE Nov 10-Aug11 With Fringe ($33,465) | | | | | | | | | | | |
| Mike Plante + others (Machinist + shop) 4%FTE ($3,000) | | | | | | | | | | | |
| Dan Zielinski + others, Graduate Students 50% FTE (4 years of project)($154,035) | | | | | | | | | | | |
| Undergraduate Students Research Assistants (800 hours at $ 10 per hour) $8000 | | | | | | | | | | | |
| **Non-capital Equipment / Tools** (Detailed breakdown of cost provided under section V on project work plan) | 3,202 | 3,202 | 0 | 5,000 | 5,000 | 0 | 18,277 | 11,215 | 7,062 | 26,479 | 7,062 |
| **Aqua Center well fix.** 25 Hp Grundfos Submersible pump with fixtures and fittings Total cost $ 20,000. This ENTF project | | | | 4,000 | 4,000 | 0 | | | 0 | 4,000 | 0 |
| **Supplies** (Fish and other experimental supplies, detailed breakdown provides under section V on project work plan) | 1,755 | 1,755 | 0 | 3,000 | 3,000 | 0 | 603 | 603 | 0 | 5,358 | 0 |
| **Travel expenses in Minnesota** (details provided in section V of project work plan) | | | 0 | 300 | 268 | 32 | 1,300 | 1,089 | 211 | 1,600 | 243 |
| **COLUMN TOTAL** | **$90,838** | **$90,838** | **$0** | **$110,300** | **$110,268** | **$32** | **$98,862** | **$91,589** | **$7,273** | **$300,000** | **$7,305** |