The Use of Turbulent Jets to Destratify the Charles River Basin

By

Jeffrey H. Church
B.S Environmental Engineering
Suffolk University, 2007

SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL
ENGINEERING IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN CIVIL AND ENVIRONMENTAL
ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2012

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Abstract

This study examines the feasibility of using turbulent jets to destratify the Lower Charles River Basin between the Longfellow and Craigie Bridges between Boston and Cambridge. The basin is currently filled with salt water that intrudes from the downstream dam and the resulting vertical density gradients inhibit mixing, leading to low levels of dissolved oxygen at depth. A physical model was scaled to a portion of this basin and salt water was used to create initial density profiles. Turbulent jets were introduced near the bottom at varying flow rates, discharge angles, and nozzle diameters, and a conductivity probe was used to document changes in salinity versus elevation and time. The effectiveness of the turbulent mixing was determined by comparing the change in water column potential energy over time, while efficiency was determined by comparing the change in potential energy versus the cumulative input of kinetic energy. The most effective arrangement provided a scaled mixing time of about a week to mix the basin. Since this is significantly shorter than the (annual) period over which stratification takes place, it is concluded that the turbulent jets would be an effective method to destratify the basin.

Thesis Supervisor: Eric Adams
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1 Background

1.1 Introduction

The lower portion of the Charles River flows through the cities of Boston and Cambridge before it drains into the Boston Harbor. A new dam replaced the original dam in 1978. The dams inhibited tidal flows and trapped saltwater behind them. The trapped saltwater created density gradients, bottom anoxia and poor water quality in the Lower Charles River Basin. The Kendall Station located on the Cambridge side of the river just downstream from the Longfellow Bridge proposed using the heated condenser water discharge to help mitigate the salinity intrusion. In 2006, this proposal was rejected by the U.S. EPA (Environmental Protection Agency) which requested that further research be done. The proposal was later (spring 2011) rejected by the Environmental Appeals Board in Washington D.C.. For this project I designed a physical model of a portion of the Lower Charles River Basin which would provide information about the effectiveness and efficiency of using outflow jets to mix the saltwater.

1.2 Charles River

The Charles River meanders 80 miles from Hopkinton, Massachusetts to Boston Harbor (Figure 1). The Boston Marathon follows roughly the same course, but more directly, covering only 26.2 miles (Hall, 1986). In 1630 the city of Boston was settled, at which time the Lower Charles River Basin was composed of tidal flats and salt marshes. The Charles River began to be used for transportation, power, and waste disposal and as the population grew much of the tidal flats and salt marshes were filled to create more land (Figure 2). As the city grew and the sewage increased, the tidal flats became noxious and were seen as a "well recognized public nuisance" (ASCE, 1981). The waste was washed out to the harbor by the river but then returned with the high tide and was deposited on the flats at low tide. Pockets of water were left behind when the tide ran out and these were perceived to be a health hazard as possible breeding spots for mosquitoes (Figure 3). As the city of Boston grew, more of the tidal flats were filled in resulting in more sewage deposited in a decreasing area of the tidal flats. This became untenable and a dam was built in 1910 to stop the tidal flows (ASCE, 1981) (Figure 4).

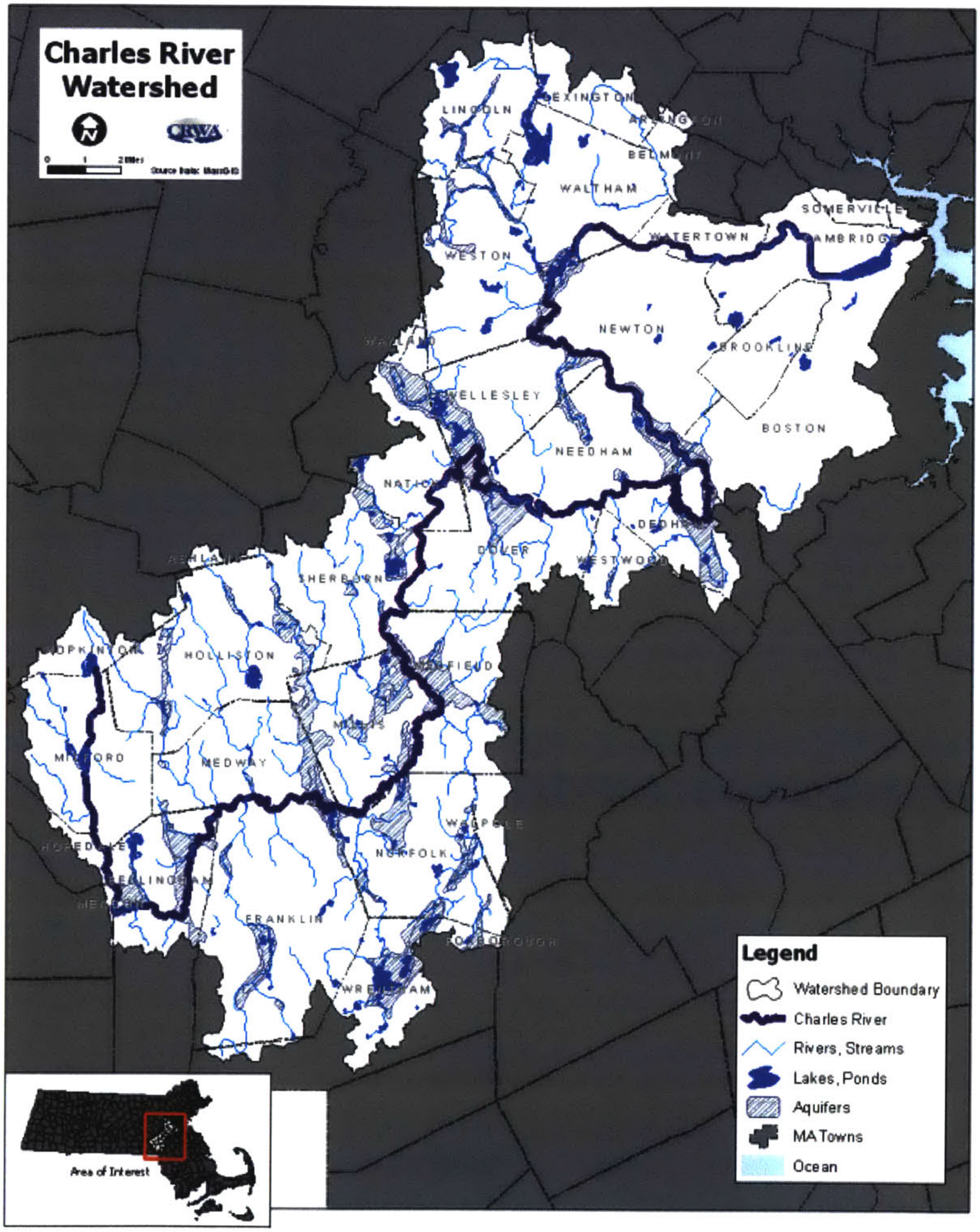

Figure 1. Map of the Charles River watershed (Charles River Watershed Association).

Figure 2. Map of Boston 1842 ("Boston" from Tanner, H.S. The American Traveler; or Guide Through the United States. Eighth Edition. New York, 1842).
http://www.lib.utexas.edu/maps/historic_us_cities.html

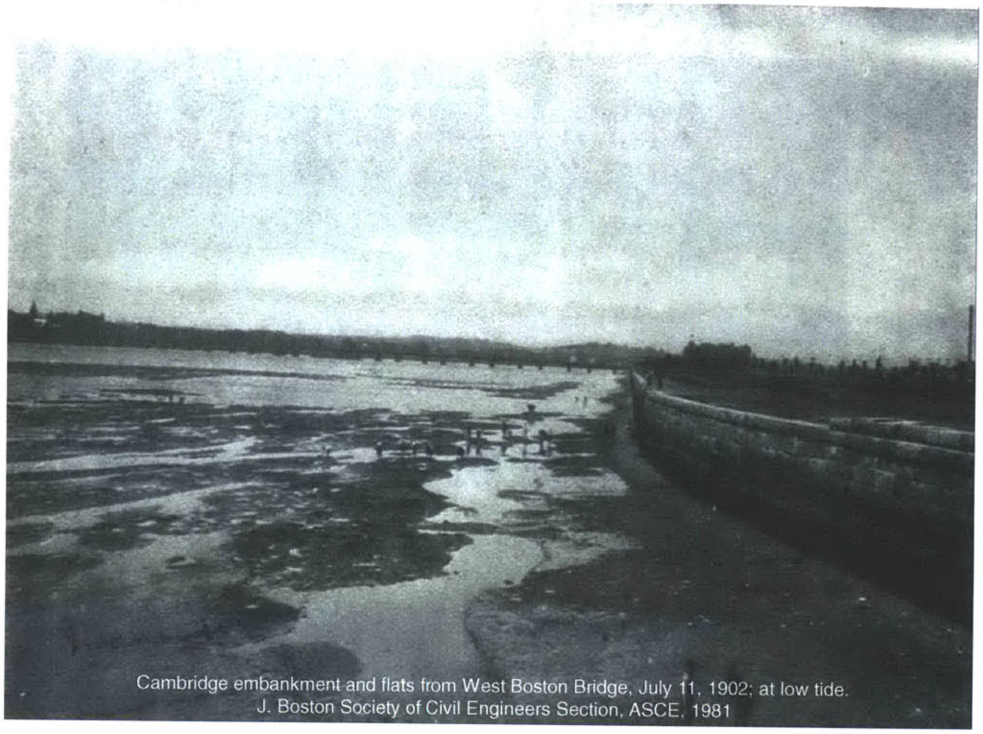

Figure 3. Tidal flat facing Harvard Bridge (Journal of the Boston Society of Civil Engineers, ASCE, 1981)

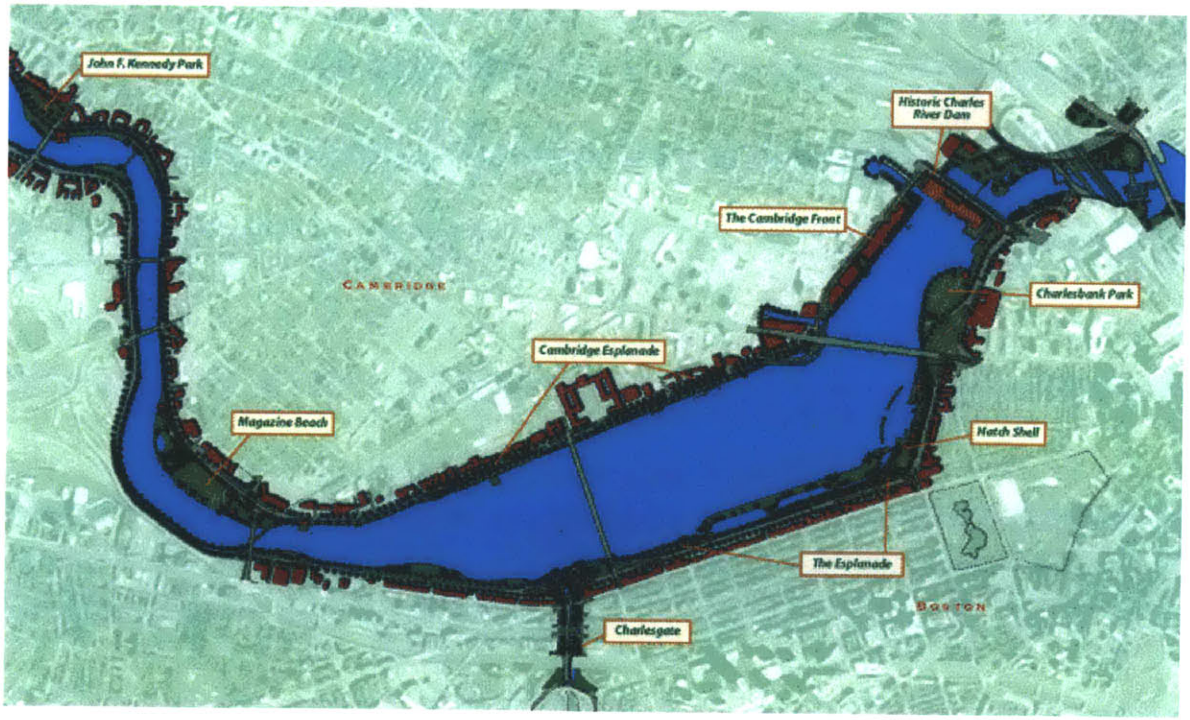

Figure 4. The current Lower Charles River Basin (http://www.lifeundersun.com)

1.3 Dams

The idea of damming the Charles River was introduced in 1859 by George H. Snelling who petitioned the Massachusetts State Legislature to construct a recreational water basin at the mouth of the Charles River (ASCE, 1981). The raw waste seen on the flats and the smell began to become a problem for the local residents. In 1891 Boston Mayor Nathan Mathews proposed to make a park system out of the area surrounding the lower Charles River and directed that several studies be made to determine the effects of damming the river (ASCE, 1981). The owners of the properties on Beacon Street which bordered the river flats intervened to stop the construction of the dam. They feared that land that would be created between their lots and the newly formed river banks could potentially obstruct their river access (ASCE, 1981). The Massachusetts State Legislature ordered the formation of a committee in 1901 to determine the "desirability and feasibility" of a dam in order to establish a park area upon the banks of the Charles River while "maintaining river traffic and diminishing the health hazards" (ASCE, 1981). The dam was approved by Massachusetts State Legislature and was completed in 1910 (ASCE, 1981). It is located at the Craigie Bridge next to the Museum of Science (Figure 5).

Major flooding occurred in 1954 and 1955 from hurricanes. The storm surges from these hurricanes as well as the amount of precipitation caused significant flooding of the Charles River. In 1968 a new dam was designed which would protect against this flooding by using large pumps to discharge the flood water into the harbor This dam was completed in 1978 and is located at New Warren Avenue underneath the Zakim Bridge (Figure 6).

The dam provides three locks to allow better access to the river for boaters and fish ladders were added as well (Hall, 1986). The recreational value of the basin was to be improved as the new dam would keep the water level more consistent and help to alleviate some of the poor water quality conditions of the Charles River (ASCE, 1981). Sluice gates were added which allowed some of the salt water to flow back into the harbor at low tide. Different sized locks reduced the influx of salt into the basin. The larger locks are used when the river traffic is high carrying multiple ships of different sizes. The smaller locks carry smaller boats and use less water from the harbor. The smaller locks are also used when river traffic is slow allowing single ships to pass with a minimum of salt water intrusion into the Lower Charles River Basin (Figure 7).

Figure 5. The old dam in 1959 (Massachusetts Department of Transportation)
http://www.massdot.state.ma.us

Figure 6. The new dam in 2008 (GMW Holdings LLC 2008)

Figure 7. Locks on the new dam (GMW Holdings LLC 2008)

1.4 Salinity Intrusion

The dam separates the harbor from the river creating a fresh water basin at the mouth of the river. This separation allows a “salt wedge” to form behind the dam. A salt wedge occurs when denser water seeps under lighter fresh water. The fresh water then flows over the salt water creating a wedge shaped formation (EPA, 1992). Salt water enters the river from leaks in the dam and the use of the locks. Every time the locks are used to transport boats, some of the harbor water is discharged into the river basin. Currently, at each Fourth of July celebration up to 5,000 boats may enter the basin from the harbor (Figures 8 and 9). This can bring over one million kilograms of salt into the river (Breault, 1999).

The salt wedge in the Lower Charles River Basin changes seasonally and from year to year (Figure 10). It also builds up over the years if it is not flushed out by a large rainfall event (Figure11). The size of the wedge peaks during the summer months from the increase in recreational boat use. This comes from the harbor water transferred to the river through the locks at the dam. The size of the wedge is reduced by high river flows which occur in the spring. Large storms are capable of flushing the salt out of the basin but these storms do not occur often. The Kendall Station is required to test the waters of the river as a condition of their NPDES permit. The testing location at the Longfellow Bridge has provided salinity profiles comparable to those modeled in my experiments. The 2006 salinity profiles of the river showed a lower layer of heavier salt water which reached up to 10 feet from bottom. Above this was a gradient of between 3 to 6 feet in height where the salinity declined to zero. The top layers were free of salt water. The curve shape of the salinity profile was consistent throughout the year, rising and falling in height according to the seasons. The gradient was created by the diffusion of salt into the fresh water at the boundary and turbulent mixing from the water flowing above the salt layer.

Figure 8. Boats on the Charles River for the Fourth of July fireworks display (Jessica Liu, The Tech)

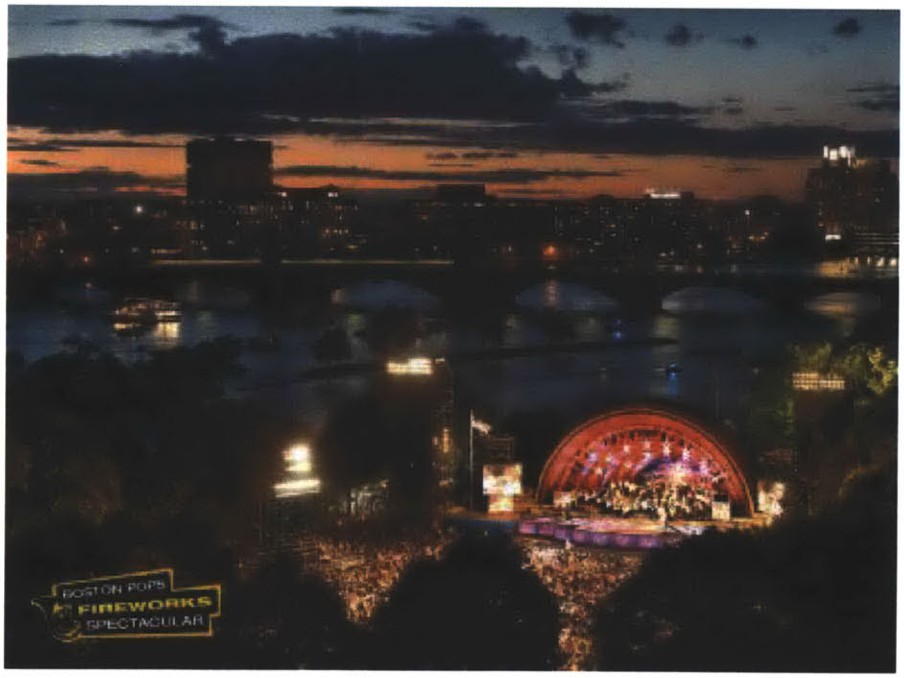

Figure 9. Boston Hatch Shell Fourth of July Celebration (http://www.wgbh.org/imageassets/boston_pops_fourth_of_july_2_620x3081.jpg)

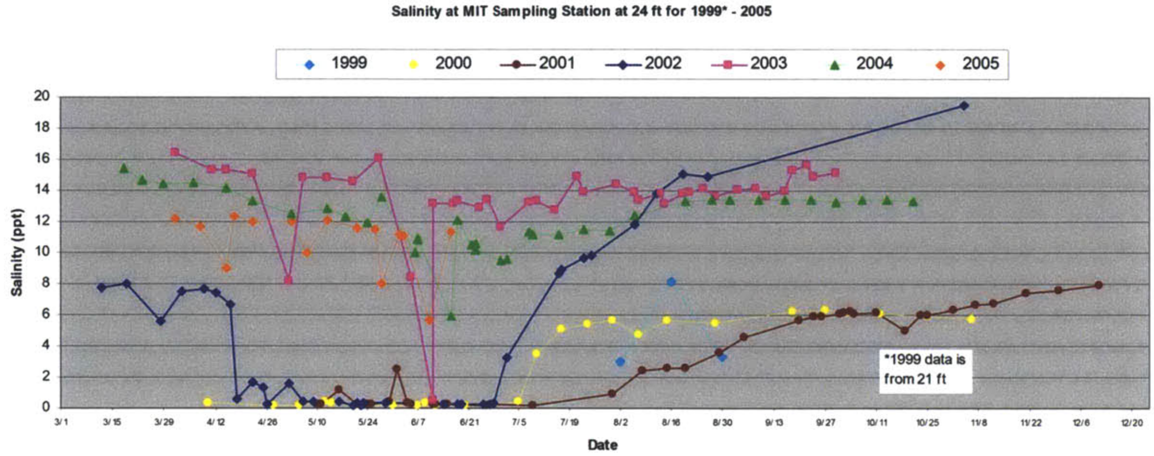

Figure 10. Yearly and seasonal variations in salinity (Normandeau Associates, Inc., 2008)

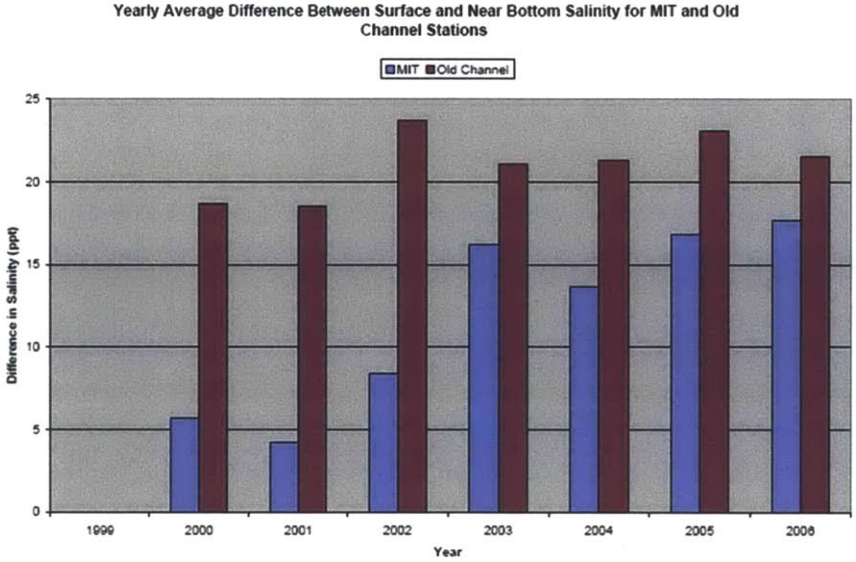

Figure 11. Yearly growth of salt-wedge (Normandeau Associates, Inc., 2008)

1.5 Water Quality

The major detrimental effect of the salt wedge is that it creates a lack of oxygen at the bottom of the river. This occurs as normal respiration of organic materials uses up the dissolved oxygen in the water which cannot be replenished due to density stratification. Rivers are normally oxygenated by mixing caused by wind, currents, and diffusion (ASCE, 1981), but the greater density of salt water on the bottom of the basin inhibits this mixing. When the river environment becomes anoxic (without oxygen) anaerobic bacteria take over the decay process producing hydrogen sulfide and other toxic chemicals. Heavy metals and an abundance of nutrients can also collect in the bottom sediments due to the lack of water flow (Breault, 2001).

In 1995, the City of Boston, the Massachusetts Department of Environmental Protection (MADEP) and the EPA joined together to make the river “fishable and swimmable” by 2005. Since 2005 the river has improved from a rating of D (some boating or swimming) to a B+ (all boating and some swimming). This is a result of closing 99.5 % of the CSO’s (combined sewer outflows) upstream. Only after a major rainstorm does enough biological contamination enter the river to render it unswimmable.

1.6 Air Bubblers

In 1978, as part of constructing the second dam, a bubbler system was installed to help mitigate the saltwater intrusion into the Lower Charles River Basin. Bubbler locations were: one above the Harvard Bridge, two between Harvard Bridge and Longfellow Bridge, and two between Longfellow Bridge and the Museum of Science (Figure 12). The bubblers were paid for by a grant which was funded by the Federal Clean Water Act and they were maintained by the MDC (Massachusetts District Commission), predecessor to the Massachusetts Department of Conservation and Recreation. The initial cost of running these bubblers was $28,000 a year (Thompson, 1999).

The bubblers worked by forcing air from pumps on the shoreline through pipes that ran along the river's bottom. Air was released through small holes in the pipe and rose to the surface. The rising bubbles created a flow of water which pulled some of the saltwater to the surface of the river. This was effective as the surrounding salt water was pulled into the upstream current. The pressure from the rising water pushed the surface waters to the shoreline where they would be pushed downward, forcing the water back to the bubblers along the river bottom. This effectively moved the salt water into the ambient river flow along the surface but did not entrain the saltwater from the dips and holes on the river's bottom.

Salinity measurements taken in the Lower Charles River Basin before and after the construction of the second dam show the effectiveness of the bubblers in reducing the size of the salt wedge. In 1977 measurements showed a distinctive salt wedge which had a high level of salinity near the dam and the salinity decreasing at a regular rate as the distance from the dam increased. Similar tests done in 1979, when the bubblers were operational, show a significantly lower amount of salinity near the dam and lower salinity throughout the Lower Charles River

Basin. The salinity levels were found to be lower throughout the Lower Basin and the salinity encroachment did not extend as far upstream as it had before the bubblers. In 1981 due to budgetary constraints the funding for the bubblers by the MDC was terminated (Thompson, 1999). This may have occurred due to the inability to see the results of the bubblers whereas other projects on the surface were more visible.

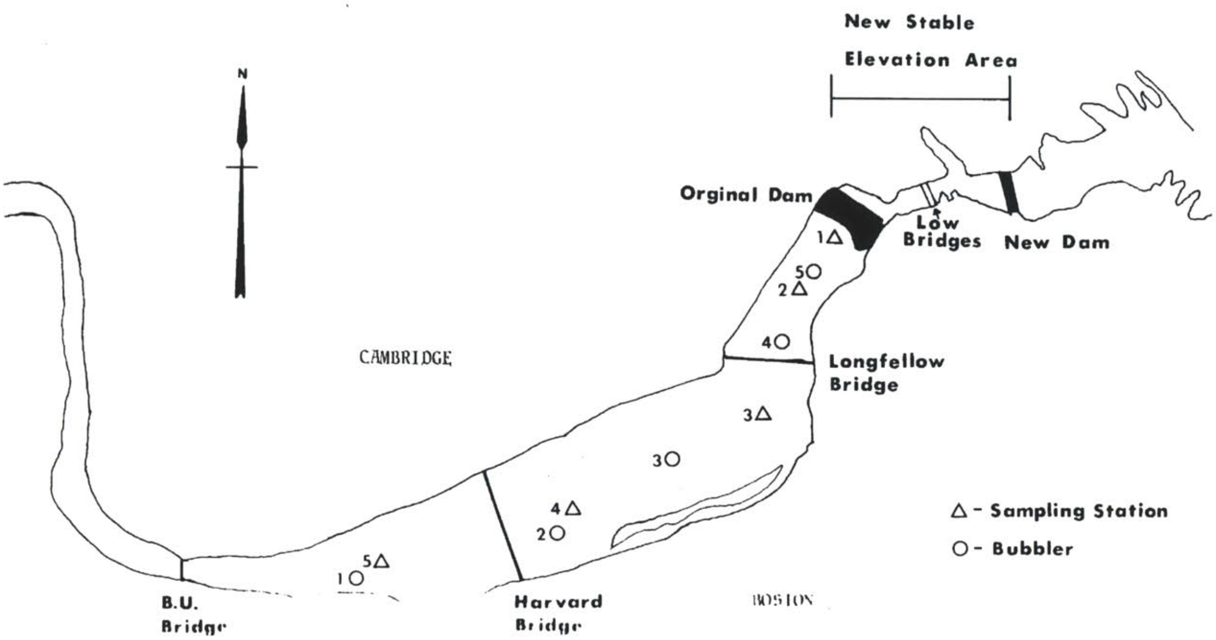

Figure 12. Map of bubblers (Godbey et al., 1981)

Figure 13. Kendall Station (Jeffrey Church, 2011)

1.7 Kendall Station

Kendall Station was built in 1949 on the site of the Cambridge Electric Company next to the Broad Street Canal (Figure 13). The plant is located on the north bank of the Charles River across from Massachusetts General Hospital. In 1988 under the conditions of the Clean Water Act the EPA issued NPDES (National Pollution Discharge Elimination System) permit MA0004898 regulating the plant's discharge into the Charles River. This allowed the plant to discharge up to 4.7 MGD of condenser cooling water into the river. Over the fifty years since its construction newer power plants were built using advances in technology which made the plants more efficient then the Kendall Station. Since it was less efficient, the Kendall Station was run only at peak times and had no trouble maintaining the limits of its water discharge permit. The plant was purchased by the Southern Energy Corporation in 1999. The company then changed its name to Mirant in 2001. In 2003 Kendall Station was upgraded to a gas powered cogenerating plant. This upgrade increased the electricity output from 113 megawatts to 256 megawatts and reduced air emissions by 41%.

This efficiency resulted from using natural gas to produce both electricity and steam. The steam was provided to the Massachusetts General Hospital as well as to buildings in Cambridge. Because it was located within the city, resistance losses from transmitting the electricity were diminished. This efficiency prompted the company to make it a baseload plant, using it at full capacity whenever possible.

In 2005, the Mirant Corporation filed for changes in its NPDES permit to take advantage of this upgrade. They proposed to install a bottom-based diffuser to discharge 35 MGD of the total. This would allow the plant to increase production without exceeding the EPA's NPDES permit requirements. The current discharge is at the surface of the river along the Cambridge shoreline (Figure 14). Placing the discharge at the bottom and extending it towards the middle of the river would provide for greater mixing of the hot water with the cold and possibly mix the lower salt layer with the fresh water flowing over it. The river flow would then push the intruding salt back into the harbor.

The EPA modified the NPDES permit by issuing a draft permit in June 2004 which allowed for the increased flow but the permit rejected the bottom-based diffuser. Public hearings were held, the proposed changes in the permit were reviewed and on September 26th 2006 a final NPDES permit was issued. The Mirant Corporation took the permit conditions to the Environmental Appeals Board in October 30th 2006. They contested the conclusions as well as the EPA's methodology. Mirant stated that the conditions of the new permit caused them a "substantial curtailment of operations" and that they "diminished their commercial viability". The Environmental Appeals Board heard arguments from the EPA, the Mirant Corporation, and the environmental groups CLF (Conservation Law Foundation) and CRWA (Charles River Watershed Association). The plant was then allowed to discharge 70 MGD providing that they take comprehensive measurements of the Charles River's conditions and fish populations during the time of the appeals hearings. On December 18th 2008 the NPDES permit was modified and another appeal was brought on February 2nd 2009.

In December 2010 The Mirant Corporation merged with RRI Energy Incorporated forming a new company called Gen-On. After losing the initial appeal, the new company decided to install back-pressure steam turbines in conjunction with air cooled condensers. These turbines are designed to discharge a portion of their waste steam at lower pressures to be used as a commercial product. The Trigen Steam Company was contracted to purchase twice as much steam when the upgrades were completed.

A new pipeline for the steam is to be built underneath the Longfellow Bridge to carry the additional steam to Boston. These new systems no longer require the flow-through cooling system and new modifications to the NPDES permit have been proposed. The discharge limit was reduced to 3.2 MGD and the diffuser proposal has been removed.

The monitoring of the river was greatly reduced as the EPA saw minimal impact to the river from the decreased outflow. The reasons for the appeals were withdrawn by all parties and new modifications for the permit were accepted on November 17th 2010. They went into effect on Febuary1st 2011. The Kendall Station's final modifications to its NPDES Permit are to be put into effect on February 1st 2016. These will remain in effect for five years until February 1st 2021, at which point they will need to be renewed.

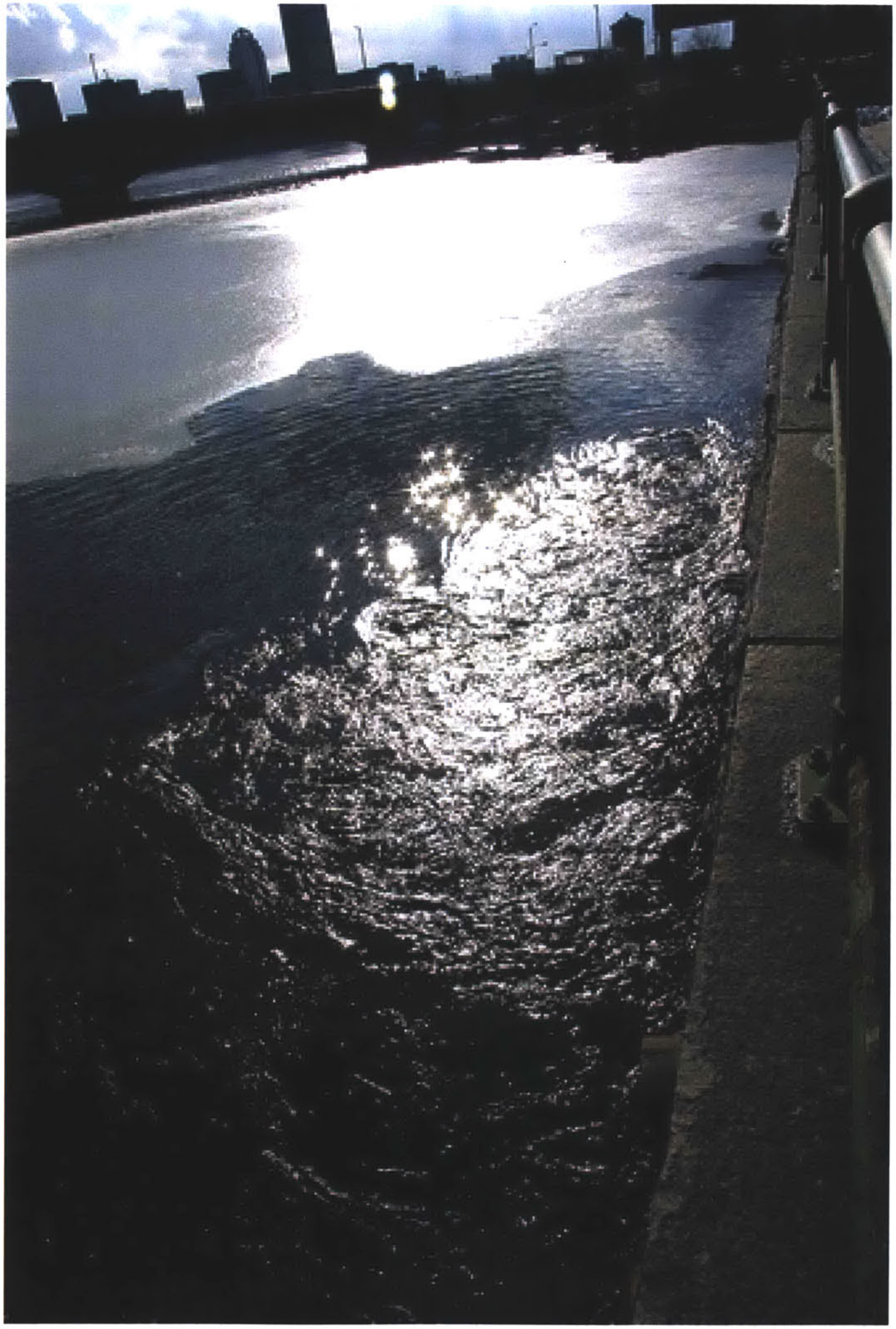

Figure 14. Plume from the surface discharge of Kendall Station (IMG_6589.JPG, Mark H Jaquith, http://www.cctvcambridge.org/node/63208, 2009)

2 Experiments

2.1 Modeling Approach

A physical model was built and scaled to represent a portion of the Lower Charles River Basin. The flow rates and the discharge rates of the jets used in the experiment were scaled to the proposed outflow from the power plant. Twenty experiments were run using different arrangements of flow rates, jet angles, nozzle sizes and number of nozzles. Conductivity measurements were taken at different depths and times. The measurements were used to determine the extent of the mixing and the changes in potential energy of the system.

2.2 Scaling

A scale model was built to represent a portion of the Lower Charles River Basin. The dimensions of this model were 213 cm (length), 91 cm (width) and 15 cm (height). The proposed diffuser prototype has 15 circular outlets each having a diameter of 23 cm. The length ratio (Lr) between the prototype (the Lower Charles River Basin) and the model was 38. The 15 cm water depth converts to a prototype depth of 5.7 m, similar to the river depths of 5-7 m near Kendall Station. To ensure kinematic similitude $L_r = U_r*T_r$ and to insure dynamic Froude scaling the Froude number = $U_r/(g_r' *L_r)^{1/2} = 1$, where; g_r' = reduced gravity ratio (taken to be one), g = gravity (981 cm/s²). Hence $U_r = T_r = L_r^{\ 1/2} = 6.2$. With the $U_r = 6.2$, the prototype discharge velocity of 3 m/s corresponds with a 48 cm/s discharge in the model. Velocities of 18 cm/s to 148 cm/s were used in the experiment. The flow rate was determined by using the relationship $Q_r = L_r^{5/2}$ so the prototype flow of 1.8 m^3/s scaled to a model flow of 202 cm^3/s. When divided by the fifteen diffuser nozzles the scaled flow rate was 13 cm^3/s for each nozzle. Flow rates ranging from 5 to 25 cm^3/s were used for the modeling experiments. The actual diffuser outlets of 23 cm were scaled to the model using the length scale of 38 resulting in a 0.6 cm nozzle size. Also used were nozzles with diameters of 0.4 cm and 0.8 cm as well as a two nozzle arrangement.

The area of the Lower Charles River Basin between the Longfellow Bridge and the Cragie Bridge is about $2.3*10^5$ m^2. The area of the model scaled to the prototype is 213 cm * 91 cm $*38^2 = 2.8*10^4$ m^2. We assume that the area mixed by a single jet is one fifteenth of the area mixed by a diffuser with 15 ports. To account for this difference, the volume of the basin was divided by 15. The result of this was A_{basin}/n (n= number of nozzles) equals $1.5*10^4 m^2$. The scaled area of the basin is then $1.2*10^5 cm^2$. The ratio of the scaled model's area of $1.9*10^4$ cm^3

to the scaled basin area of $1.2*10^5 cm^2$ is then found to be 6.3. Thus we expect the approximate mixing time of the prototype to be 6.3*6.2=39 times the model's mixing times.

2.3 Equipment

The tank constructed for this experiment measured 213.5 cm by 91.5 cm by 20 cm. The 20 cm depth allowed the tank to be filled to approximately 15 cm which is comparable to the depth of the river using a length scale of L_r=38 (Figure 15). The sides were built of ¼" Plexiglass with the base being ½" Plexiglass. A sluice gate of ¼" Plexiglas was made to facilitate the creation of salinity profiles. Salt water with a known concentration was placed on one side and fresh water was placed on the other side (Figures 16, 17, and 18). When the sluice gate was removed, the denser salt water slipped under the lighter fresh water (Figure 16). There was some mixing at the interface which settled to a profile similar to that within the Lower Charles River Basin (Figure 17 and 18).

A peristaltic pump (model # 7521-40) with pump head (model # 77250-62) from Cole-Parmer Instrument Company was used to pump water from an "intake" behind the jets at flow rates from 5 to 25 ml/s. A peristaltic pump is a positive displacement pump that uses rolling bearings on a wheel to push fluids through flexible tubing. This was selected as it provides a steady flow and allows the fluids to remain untouched by the pumping mechanism. The pump was calibrated to determine the flow rates provided by different settings (Figure 23).

A Thermo Scientific Orion 3 Star portable conductivity meter was used to record conductivity and temperature. Conductivity was accurate to 0.01 mS (microSeimens) for readings up to 10 mS and accurate to 0.1 mS for readings up to 50 mS. The meter was calibrated before each experiment according to the manufacturer's specifications.

The conductivity probe was a Thermo Scientific 3005 MD conductivity cell. This had a Dura Probe 4 electrode conductivity cell which was made of epoxy graphite and measured 6" long and

½" in width. The probe was contained in a harness that allowed for accurate 1 cm depth measurements. The harness held the probe in place by using two wood plates measuring 2" by 2" and bolted 1" apart. Holes were drilled in the center of the plates to hold the probe vertical to the surface.

A stand was constructed for the probe harness which allowed measurements to be taken anywhere within the tank. Two supports 3 ½ feet long were connected together forming a platform upon which the harness could move freely along the width of the tank. Holes placed into the side of the stand allowed the harness to be raised and lowered in 1 cm increments.

Cargill Top-Flo Salt was used to create the saltwater solution. This is a high grade salt used for food manufacturing. It contains 99.89% Sodium Chloride and the anti-caking ingredient prussiate of soda (Sodium Ferrocyanide Decahydrate). Bromphenol Blue Sodium Salt was usually used as a dye. This was purchased from GFX chemicals. It was chosen for its intensity of color and that it would be neutral in regard to the readings. McCormick Food Color and Egg Dye and Indian Tree Natural Decorating Colors were also used to obtain different contrasts of the mixing.

To show the effect of changing the discharge jet angle, a support block was constructed. This support had a square base measuring 2.5 cm by 2.5 cm. Its height was 1.25 cm on one side and 2.5 cm on the opposite side, resulting in a 26.6° angle. To create a 45° angle the discharge jet was attached to the higher side of the support and then attached to the bottom of the tank at a distance of 2.5 cm from the support block (Figure 18). For the 0° angle, the support was placed on its side and the jet attached to the top. The jet was attached to the angled top of the block to provide the 26.6° discharge (Figure 19).

A U-shaped joint was used to split the flow into two jets. The flows from each jet were measured to ensure both jets produced an equal discharge. These were distanced 3 cm apart to insure that the flows did not interfere with each other. The two nozzles were attached to a horizontal support which kept them at the same angle and parallel to each other. The two-jet support was attached to the support block to provide the same angles as the one-jet flows.

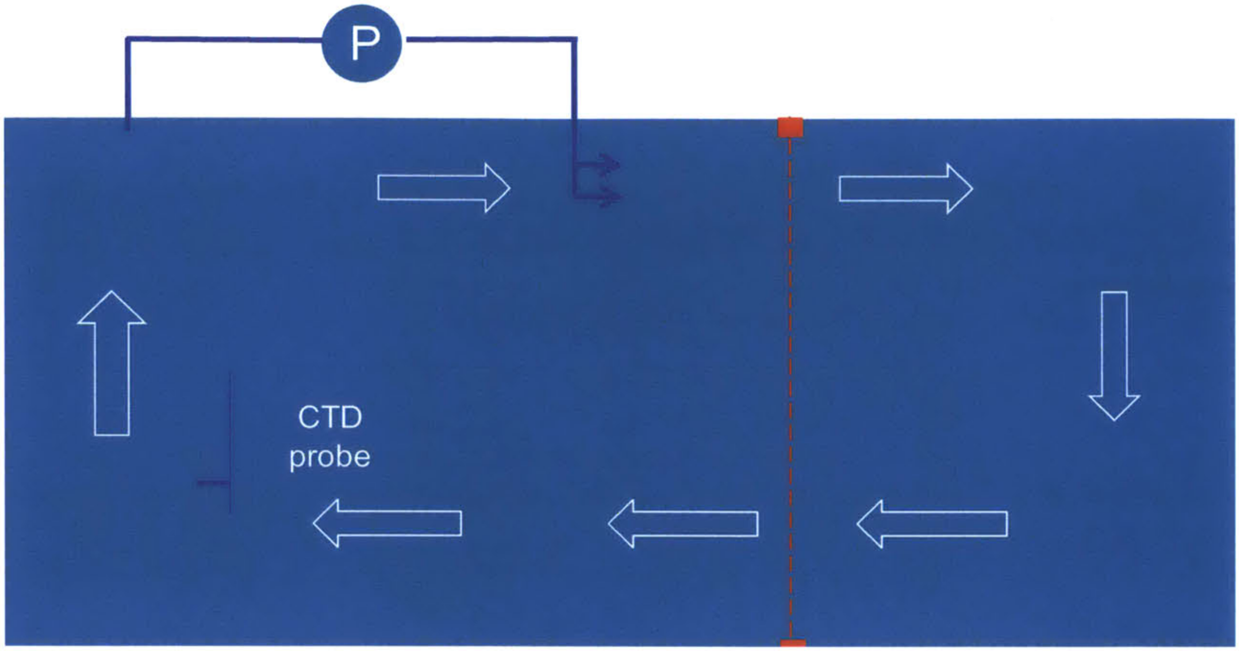

Figure 15. Diagram of model tank

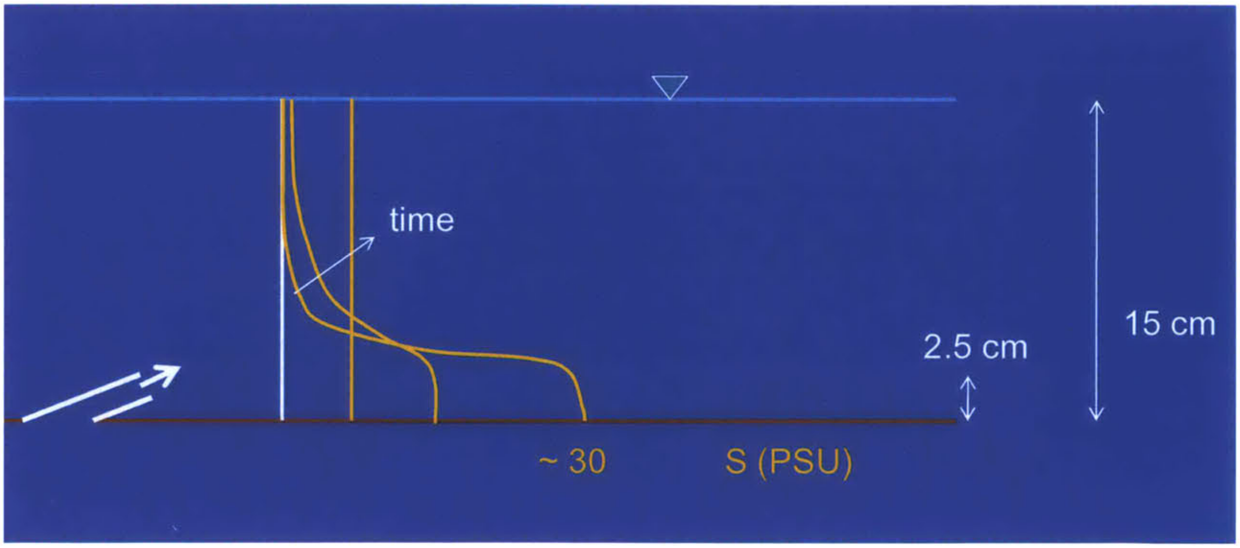

Figure 16. Side view diagram of tank and change in salinity profiles.

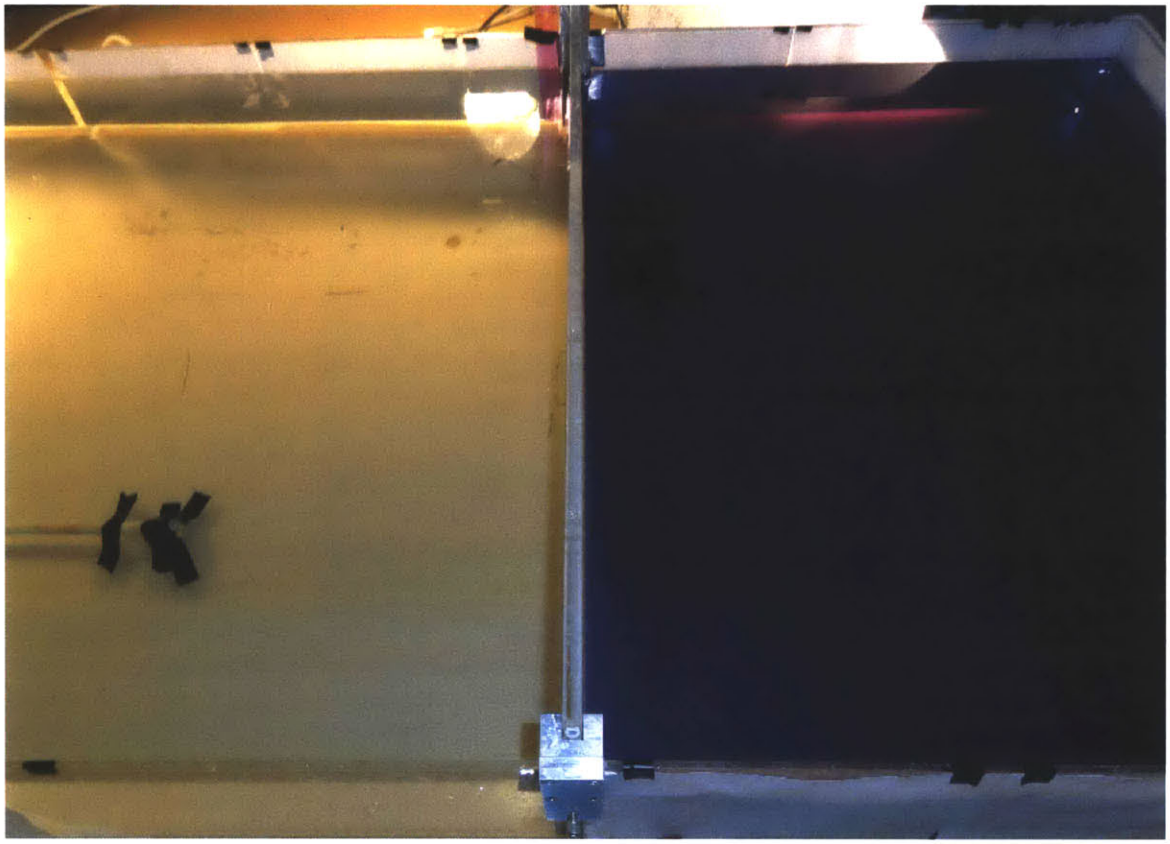

Figure 17. Side view of separating fresh water and purple saltwater before mixing

Figure 18. Side view of sluice before mixing (picture cropped at surface)

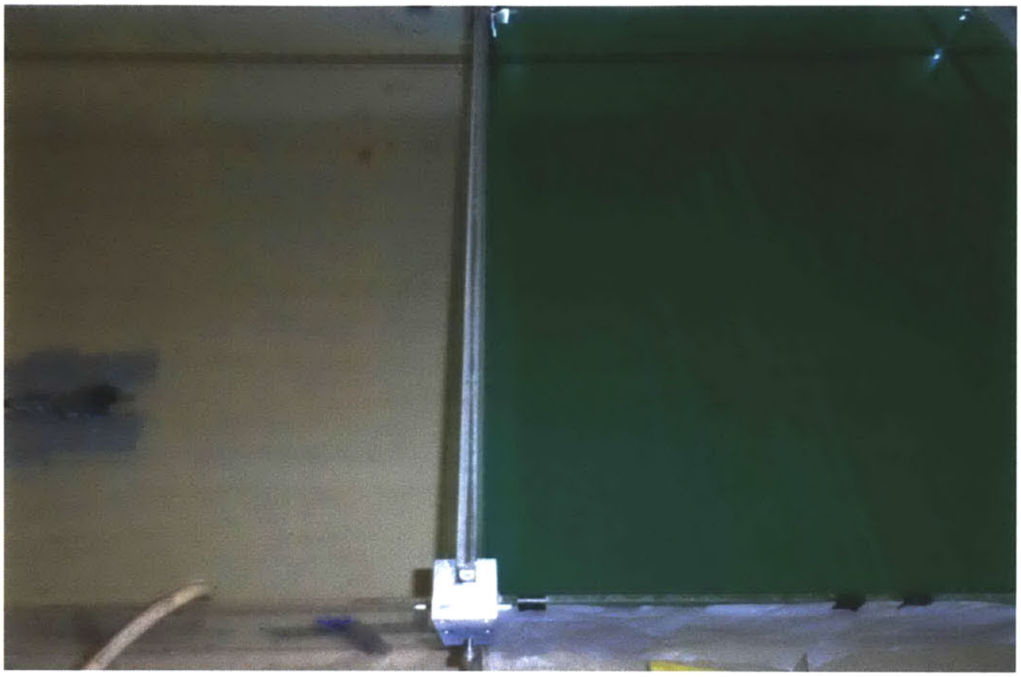

Figure 19. Top view of separating fresh water and green saltwater before mixing

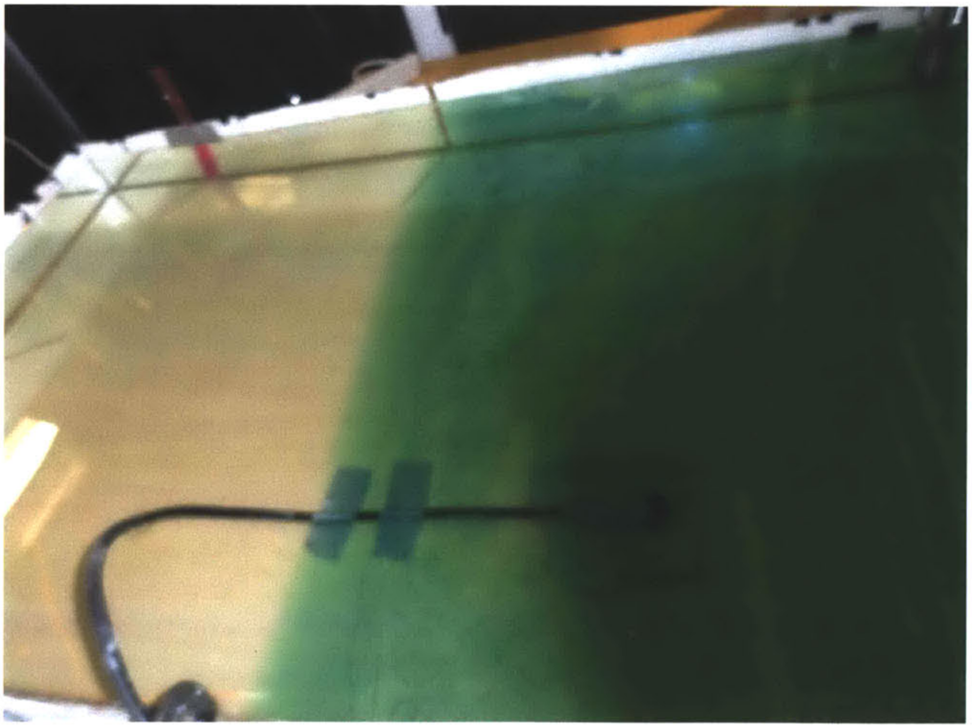

Figure 20. Tank mixing after sluice is removed

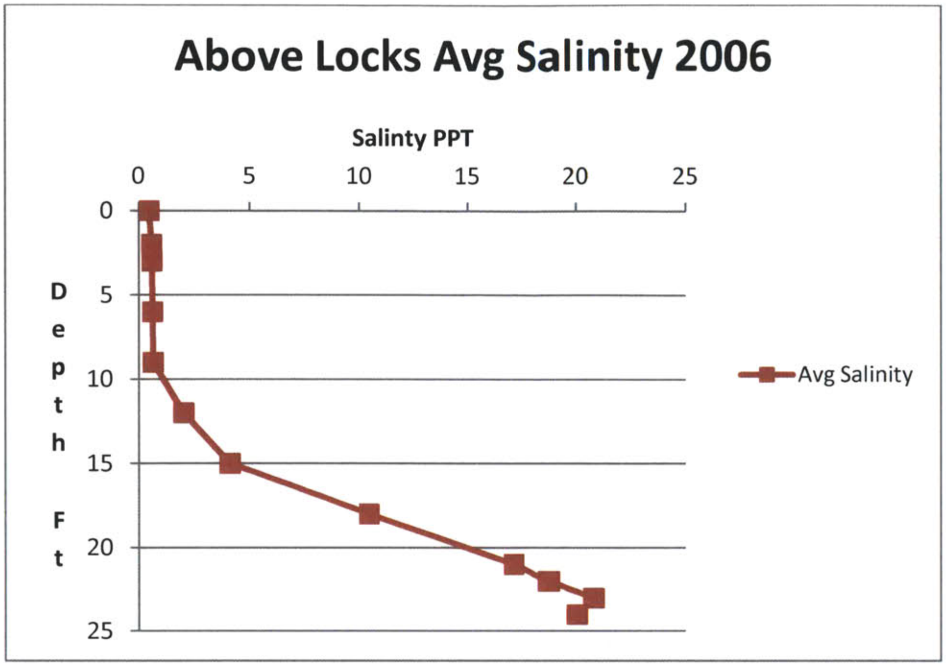

Figure 21. Yearly average of the salinity profile for above the locks in 2006.

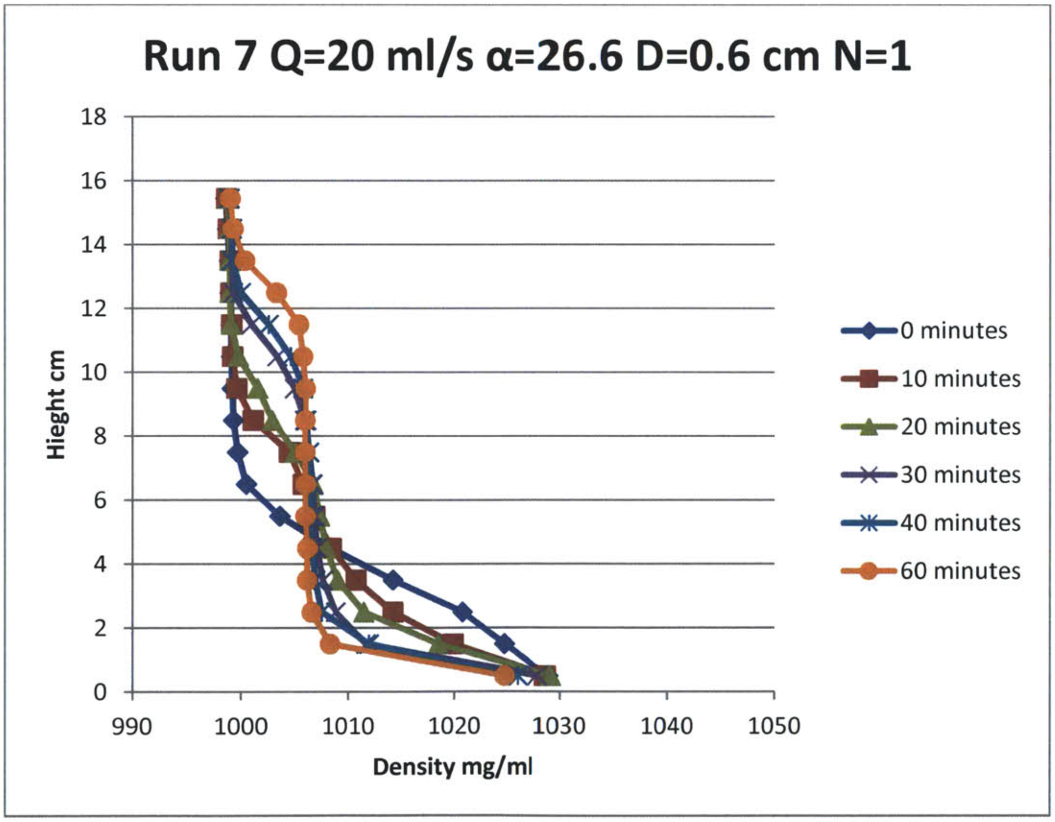

Figure 22. Salinity profile for experimental Run 7

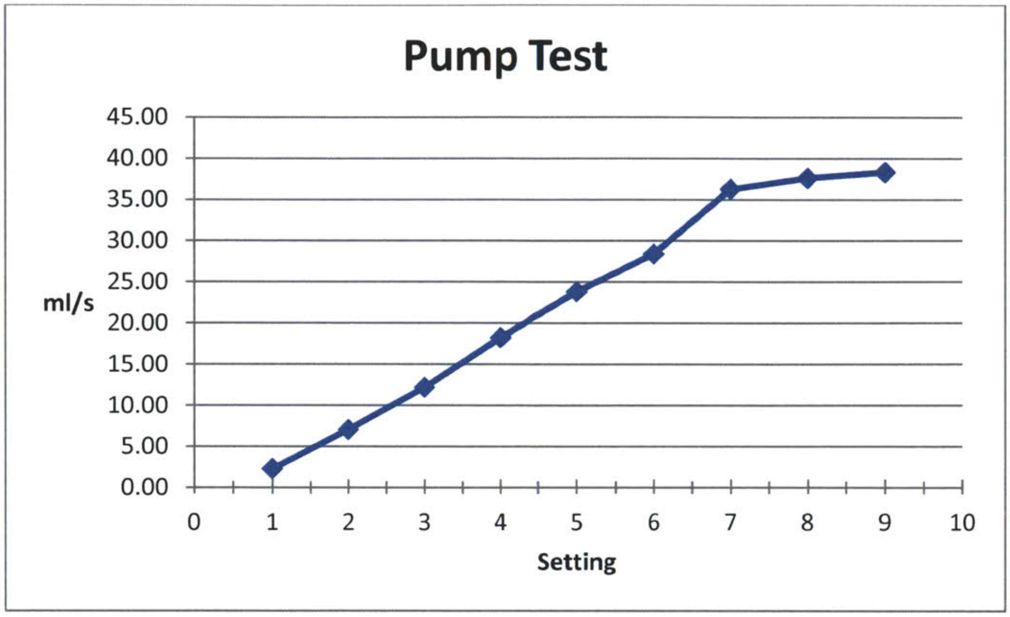

Figure 23. Calibration of peristaltic pump

Figure 24. Single port with a 45° angle (picture cropped at surface)

Figure 25. Single port with a 26.6° angle

2.4 Procedures

The experiment began by creating a salinity profile representative of the Lower Charles River Basin. Eight to ten buckets of mixed saltwater were used to create a solution of about 30 ppt (parts per thousand) in the smaller side of the tank, about 1/3 of the total volume. As the fresh water flowed into the larger side of the tank, the buckets of saltwater were added, keeping the fresh water approximately 1 cm higher than the saltwater. This was done to avoid any salt water intruding into the fresh water. Dye was added to the saltwater to track any leakage and to enhance the observations of changes in the salinity profile (Figures 17 and 19).

The sluice gate was placed in the tank 71.2 cm from one end, dividing the tank into sections of 1/3 and 2/3 of the tank area. The 1/3 area section contained the heavier 30 ppt salt solution which would slide underneath the lighter fresh water when the sluice gate was removed creating the stratification. The salt and fresh water mixed slightly when the sluice was removed resulting in a salinity gradient similar to that found in the river. The sluice was removed and the salt water flowed under the fresh water. Some mixing occurred resulting in a gradient of 2 or 3 cm at the border of the salt and fresh water. The tank was then given 60 minutes to settle.

The probe was calibrated using the 12.0 mS solution following the calibration instructions. The probe was placed in the probe harness and the conductivity and temperature readings were taken at 1 cm intervals for the 15 cm depth of the tank. The probe was then removed from the tank and the pump was run for ten minutes (Figures 26 and 27). The pump was then turned off and 5 minutes were given to allow the system to settle which created a horizontally uniform vertical salinity profile throughout the tank. The probe was rinsed and the procedure repeated after another 10 minutes of pumping. Most experiments received 60 minutes of pumping.

Most runs were made in both "continuous" and "batch" modes, as described above, but a few were run in "continuous" mode. The continuous method of testing allowed the jets to continue running as the conductivity measurements were made. The readings were taken every 30 seconds at 1 cm depths in the water column. The tank was divided into four quadrants and the readings were taken from the middle of each quadrant. This method provided a representation of how the salinity was transported in the tank but required interpolation between the times to compare the results. The interpolation was done by graphing the known conductivities and then taking the plotted results at 10 minute intervals.

The salinity profiles varied over the area of the tank. As expected the quadrant closest to the jets had the greatest mixing while the quadrant furthest from the jets had the least. The readings fluctuated significantly in the first quadrant where the turbulence was greatest.

The static (batch) method of experimental readings required more time but showed the effectiveness of the jet's mixing in a clearer fashion. Stabilization was confirmed visually from dye that had been added to the saltwater as a guide. Three layers of freshwater, mixed water, and saltwater could be clearly seen with the dye. The batch method was selected for all runs which are analyzed here.

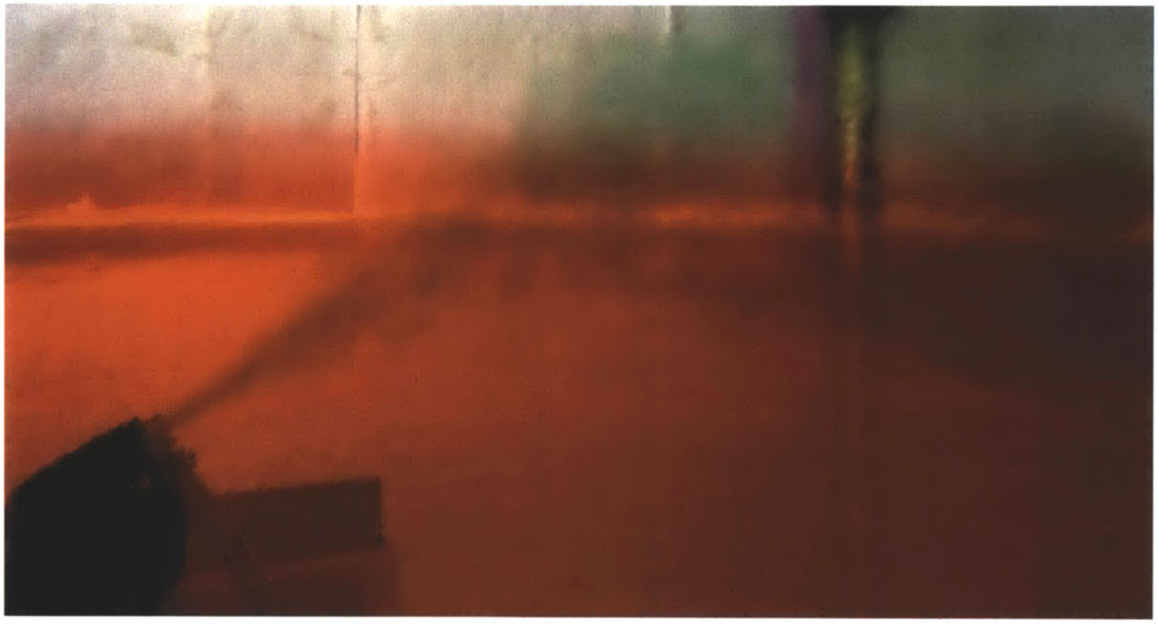

Figure 26. Initial green flow into orange stratification (picture cropped at surface)

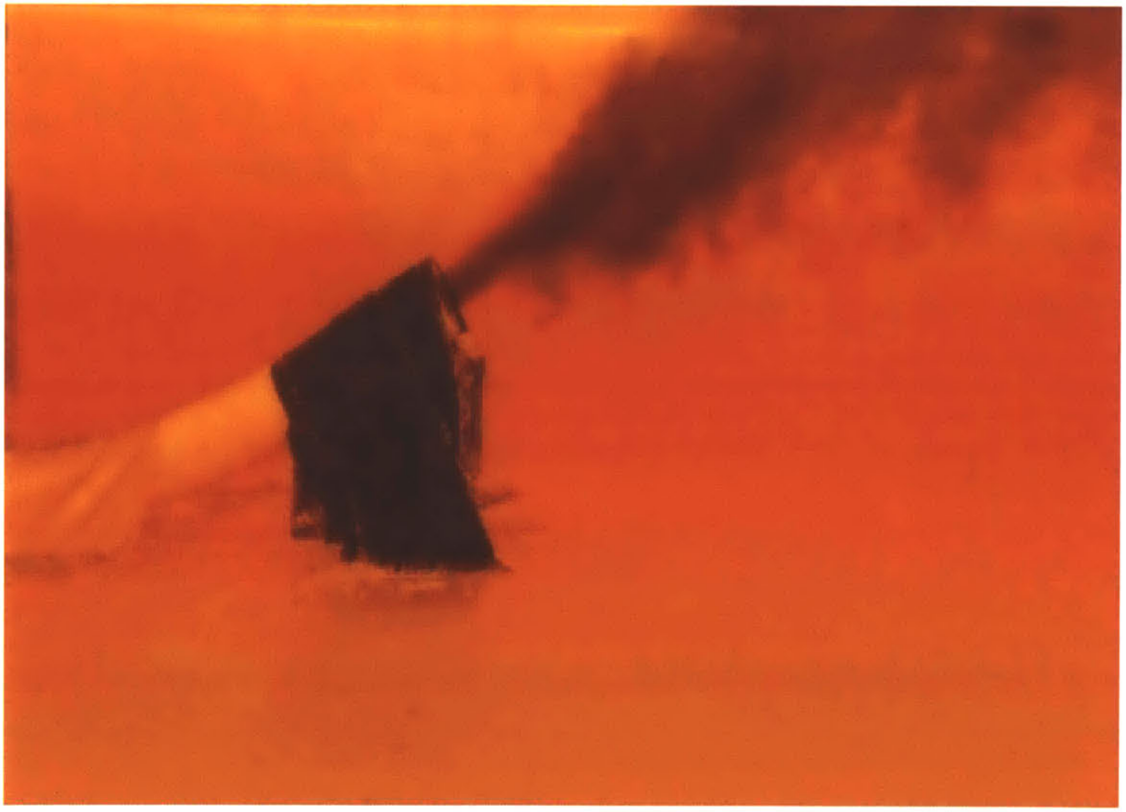

Figure 27. Initial red flow into orange stratification

3 Analysis

3.1 Initial Potential Energy Deficit

Density profiles were collected to determine the changes in potential energy during the experiment. The testing probe and meter provided conductivity and temperature readings which were then converted to density. The conductivity and temperature readings were converted to salinity using the online conversion found at www.fivecreeks.org. The salinity and temperature were then used to find the density (ρ) using this formula (McCutcheon et al., 1993):

$$\rho=1000*(1-(T+288.9414)*(T-3.9863)^2/508929.2*(T+68.12963))+A*S+B*S^{1.5}+C*S^2$$

$$A=0.824493-0.0040899*T+0.000076436T^2-0.00000082467T^3+0.0000000053675T^4$$

$$B=-0.005724+0.00010227T-0.0000016546T\hat{}2$$

$$C=0.00048314$$

where T = temperature in centigrade

S = salinity in parts per thousand.

Potential energy of an object is calculated as the mass of the object times gravity times the height of the center of mass above a fixed point:

$$PE=m*g*h$$

where m = mass in grams

$g = 981\ \mathrm{cm/s^2}$

h = height in cm.

To determine the potential energy of a column of saltwater, we integrated the mass over the height, choosing $z=0$ for the bottom and $z=H$ for the top. The integration was replaced by a summation using an interval Δz of one centimeter:

$$PE = \sum_{i=1}^{N} \rho * g * A * h * \Delta z$$

where ρ= density of water at height h in gm/cm^3

A = area of the tank in cm^2

g = 981cm/s^2

A stability index (SI) was used to normalize the measurements. This index shows the difference in PE between a fully mixed water column and an equivalent stratified water body. The SI can be shown to be given by:

$$SI = \sum_{1}^{H} \big(\rho(avg) - \rho(z)\big) * (z - zc) * g * A * \Delta \mathrm{z}$$

where ρ = density in gm/cm^3

zc = height of the center of gravity

Δz = change in height of water layer in cm

ρ(avg) = average density of the fully mixed system in gm/cm^3.

At the start of the experiment the salinity profiles were similar to those of the Charles River. The effectiveness of the discharge jet in destratifying the basin was measured by how close the profile came to the well-mixed condition. The fully mixed potential energy of the system was found by averaging the densities of the system found at each time period to determine an average density for the system. This average density (ρ(avg)) was then used to find the fully mixed potential energy:

PE (fully mixed) = ρ(avg)*A*H*g.

3.2 Time Variation of Kinetic and Potential Energy

Kinetic energy (KE) is the amount of energy contained within movements of mass. This is calculated by multiplying one half of the mass by its traveling velocity squared:

$KE = ½*m*V^2$

where m = mass in gm

V = velocity in cm/s.

In this experiment the mass was found by multiplying the density of the discharge water ($\rho=1$) by the discharge flow rate and the duration of the flow:

$m = \rho*Q*t$

where $\rho = 1 gm/cm^3$

Q = flow rate in cm^3/s.

The velocity is found by dividing the flow rate by the area of the nozzle:

$V = Q/A$

where Area = $\pi*r^2$ in cm^2

r = radius of nozzle in cm.

The kinetic energy of each run was varied by changing the flow rates and nozzle sizes. Changing the number of nozzles or the angle of the discharge did not affect the kinetic energy. When the flow rate was increased, the amount of kinetic energy increased. When the nozzle radius was increased, the amount of kinetic energy decreased.

To account for uncertainty in the measured conductivity, the mass of the system initially and the recorded mass found during the experiment were scaled. This was done by taking the recorded mass of the system and dividing it by the initial mass to determine a scaling factor.

This scaling factor was used to adjust the mass in a similar manner for all of the experiments. The mass of the experiment was determined by multiplying the density of each 1 cm layer of water by that layer's area and then adding together the mass of all the water layers:

$$mass = \sum_{i}^{N} \rho * g * A * \Delta z$$

An adjusted salinity was found by multiplying the recorded salinity by the scaling factor. The adjusted salinity was then used to determine a scaled density.

To determine the mixing times of the different arrangements the changes in the stability index were plotted vs. time. An EXCEL exponential regression function was applied to the plots resulting in this formula to describe their behavior:

$$y = A * e^{-k*t}$$

Where y = 1- the change in the stability index

A = constant (taken to be one)

e = exponential function

t = time

k = exponential constant.

The reciprocal of the exponential constant shows the characteristic mixing time for the discharge.

The jets mix by pumping (entraining) water. Depending on the length of their trajectory, and the strength of mixing, the amount of water can exceed the amount that is discharged by a significant quantity. We define the ratio of the pumped water to the discharged water as the dilution factor (S). If the mixing occurred by pure displacement, as in plug flow, the mixing time would be the hydraulic residence time given by $T_{hyr}=V/Q$. The dilution factor is determined by dividing the hydraulic residence time by the experimentally determined mixing time (reciprocal of k) or $S_{experimental} = V/Q^{*}t_{experimental}$.

3.3 Efficiency

Efficiency is the amount of usable work created in relation to the energy provided. In this experiment efficiency is the amount of potential energy gained by the system compared to the amount of kinetic energy introduced. By mixing the tank, denser water gets pulled to a higher layer in the water column which raises the potential energy of the system. The jets provided the kinetic energy. The different discharge arrangements can be determined by their efficiencies:

Efficiency = $\Delta PE/\Delta KE$
Where PE = potential energy
KE = kinetic energy.

The efficiency was generally the highest at the start of the experiments and then tapered off over time. As the water column became more mixed it took more energy to move the salt water up the water column. The rate of increase in kinetic energy remained constant while the rate of increase in the potential energy was reduced.

3.4 Comparisons

The flow rates used for the experiments were 5, 10, 15, 20 and 25 ml/s. By increasing the flow rates through a nozzle of fixed dimensions the outflow velocity increased which in turn increased the kinetic energy of the system. Raising the velocity from 5 to 25 ml/s raised the kinetic energy 125 times. Increasing the flow rates was directly proportional to the entrainment of the surrounding fluid into the jet stream. More of the saltwater was brought up to the higher layers of the water column as the flow rate was increased. Turbulent mixing was increased as the near field mixing zone became extended by the greater flow rate.

Increasing the discharge could create a scouring of the bottom, removing some of the sediments. Boiling could occur if the discharge reached the surface which would waste some of the energy of the jet

Three different angles were used for the discharge: 0^o, 26.6^o, and 45^o (Figures 24 and 25). With the 45° angle some of the jet's energy was lost by the jet's reflecting off the surface (Figure 28). At the lower flow rates the stratification presented a barrier to the jet reaching the surface (Figure 29). As the stratification was mixed into a gradient, the efficiency increased. At 0^o the jet's energy was mostly used to push the water around the tank. This created some mixing, but did little to move the saltwater up the water column. The higher flow rates presented a danger of scouring although the dense bottom water would have to mix first (Figures 30 and 31).

Initially, partially mixed water would be moved higher into the water column over time. As the level of partially mixed water approached the surface, the rate of mixing decreased. A fully mixed salinity profile is vertical with the salinity being equal at all levels while a stratified profile is horizontal with the salinity being lower in the top layer than in the bottom layer. The use of turbulent jets to mix the stratified water moved the horizontal profile into a vertical profile. This occurred first in the middle of the profile and then gradually the gradients at the top and bottom were reduced. As the vertical part of the profile grew in length, the mixing became less efficient and the mixing times increased. As the salinity decreased in the lower levels the entrained salt was reduced, resulting in less salt being carried up the water column as the mixing progressed. The result of this was that initially there was a period of efficient mixing as the depth of the stratification reached the depth of the discharge jet. The salinity gradient increased in size gradually reaching the surface. This corresponded with a decrease in efficiency as the gradient rose in height.

The middle layers of the water column became fully mixed before the top or the bottom layers. As the fully mixed layer increased in size the efficiency was further reduced. The heavier lower water was entrained into the jet's flow and mixed, then the fully mixed water was deposited at the top of the fully mixed layer. The fully mixed layer descended in the water column to fill the layer of the removed heavier water. This gave the appearance of the middle fully mixed layer growing at the top and the bottom but it was really growing at the top and descending as it grew.

Figure 28. High flow reflecting off of the surface (picture cropped at surface)

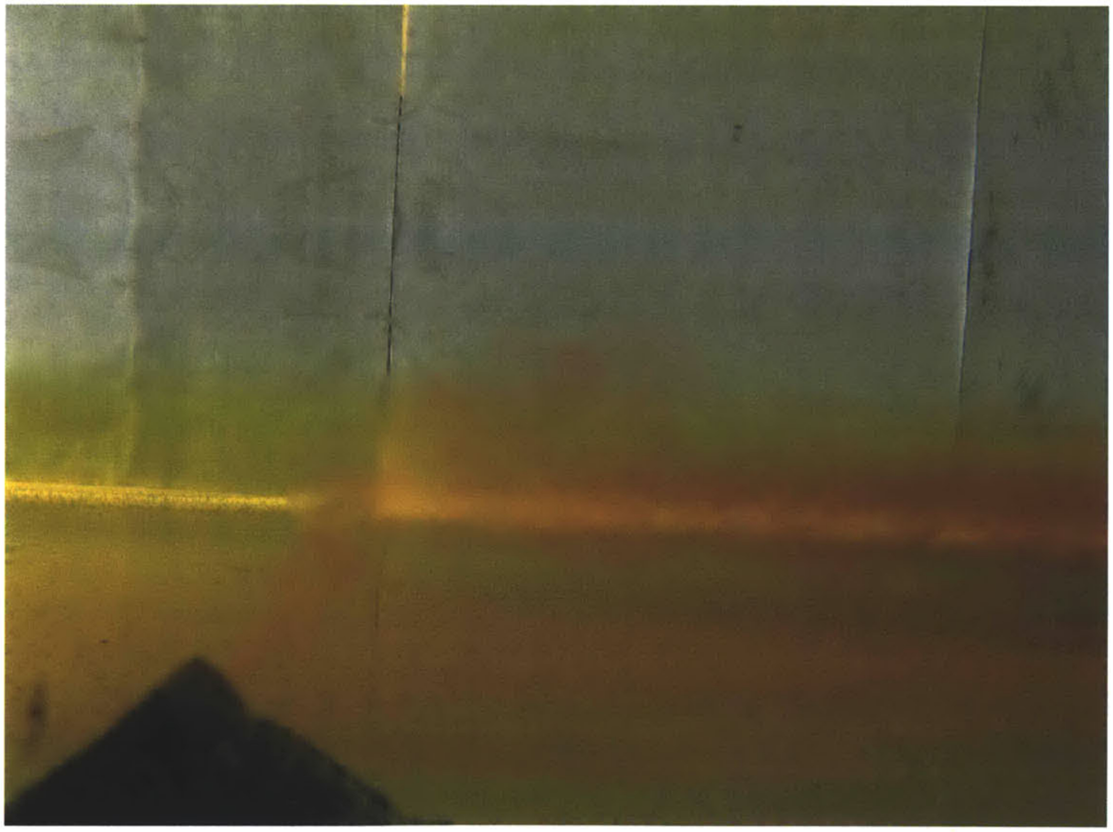

Figure 29 Low flow inhibited by density stratification

Figure 30. Fully mixed green top layer with orange bottom layer unmixed (picture cropped at surface)

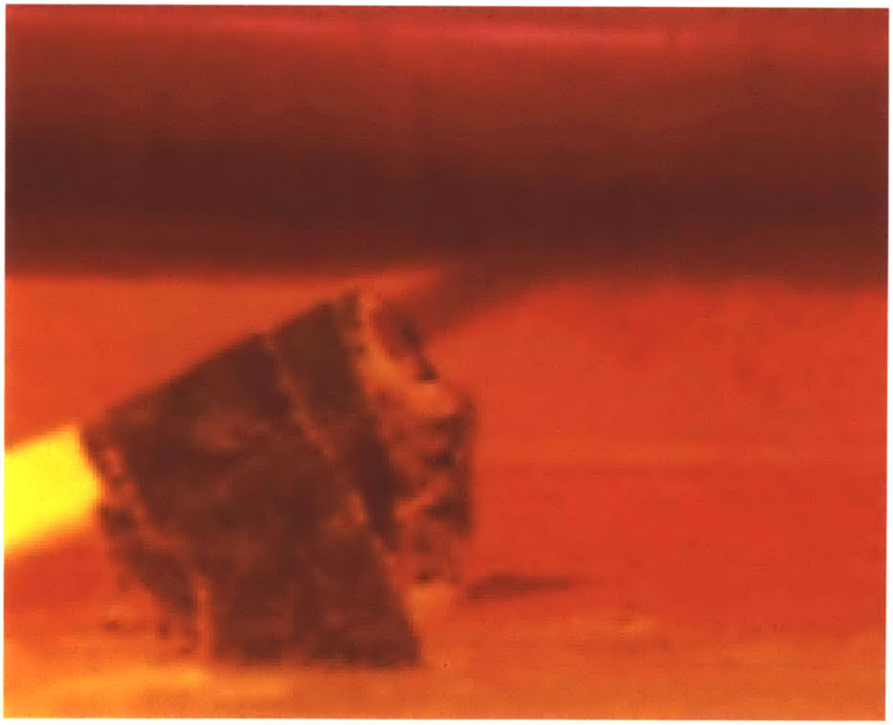

Figure 31. Fully mixed red top layer with orange bottom layer unmixed

3.5 Discussions

The graph in Figure 32 is of the changes in the normalized potential energy of a 20 ml/s flow when the angles of the jets are varied. The flow with a 0 degree angle produced the least amount of potential energy gain and the angle of 26.6 degrees produced slightly more potential energy then the flow at the 45 degree angle. The zero degree angle did not push the heavier water up into the water column effectively.

Figure 33 is another normalized potential energy graph showing the differences by the flow rates with the jet angled at 26.6 degrees. The potential changes are directly related to the flow strength with the higher flows having the most change in potential energy and the lower flow rates having the least potential energy change. By increasing the flow rate, the velocity of the flow was increased which allowed the jet to entrain more water.

Figure 34 is a graph of the efficiency of the jets when the flow rate was 20 ml/s. The angles of the jets were varied. The 26.6 degree angle had the most efficient flow and the 0 degree angles jet has the worst efficiency. The 45 degree angle jet reflected off of the surface which reduced its efficiency.

Figure 35 shows the efficiency by varying the flow rates and keeping the angle at 26.6 degrees. The efficiency is highest with the lowest flow rate of 5 ml/s and the efficiencies decrease as the flow rates increase. Increasing the kinetic energy does not have an equal increase in potential energy.

Figure 36 is a comparison of the changes in potential energy in relation to the nozzle diameter size. The flow and angle were kept constant at 20 ml/s and 26.6 degrees. The smaller nozzle size of 0.4 cm created the highest potential energy change and the largest nozzle size of

0.8 cm had the lowest change in potential energy. This occurs because the size of the nozzle diameter directly influences the velocity of the nozzle discharge.

Figure 37 is a graph of the efficiency differences when the nozzle sizes are varied. The flow rate was 20 ml/s and the angle was 26.6 degrees. The efficiency increased with the larger nozzles size. Increasing the nozzle size reduced the kinetic energy, which resulted in an increase in the efficiency.

Figure 38 is a graph of the k values (in reciprocal minutes) found by doing an exponential regression on the normalized potential energy curves. The 26.6 degree angle and the 45 degree angle have higher values than the 0 degree angle. This shows that upward angles decrease the mixing times. The 26.6 degree angle had a slightly higher value then the 45 degree angle which could be attributed to the latter reflecting off of the surface.

Figure 39 is a graph of the mixing times (reciprocal k) of the model by flow rates and angles. The mixing times are rather similar when the flow rates are 15 ml/s or more. The zero degree angle's mixing time increases sharply at flows under 15 ml/s. The other angles mixing times increase as well when the flow rate decreases, with the 45 degree angle's mixing time increasing faster than the 26.6 degree angles mixing time.

Figure 40 is a graph comparing the reciprocal k values in minutes of different nozzles sizes. With the flow of 20 ml/s and angle of 26.6 degrees, the reciprocal k value decreased with the increasing size of the nozzle. This shows how the increased area of the nozzle discharge reduces the kinetic energy and subsequently increases the mixing time.

Figure 41 is a graph comparing the exponential regressions of one or two nozzles. With a 10 ml/s flow rate and an angle of 45 degrees, the reciprocal k value of the jets is similar. This is a result of the decrease in individual flow rates per nozzle corresponding to the increase in total area of the discharge jets.

Figure 42 is a graph showing the dilution factors of the different flow rates and angles. The zero degree angle has the lowest dilution rates because it fails to use the entire water column for mixing. The 45 degree angle at the lower flow rates has higher dilution factors then the 26.6 degree angle because the flow rate is not yet high enough to be sufficiently constrained by reflecting off the surface. The 26.6 degree angle has the highest dilution factors at the higher flow rates as it uses the water column most effectively.

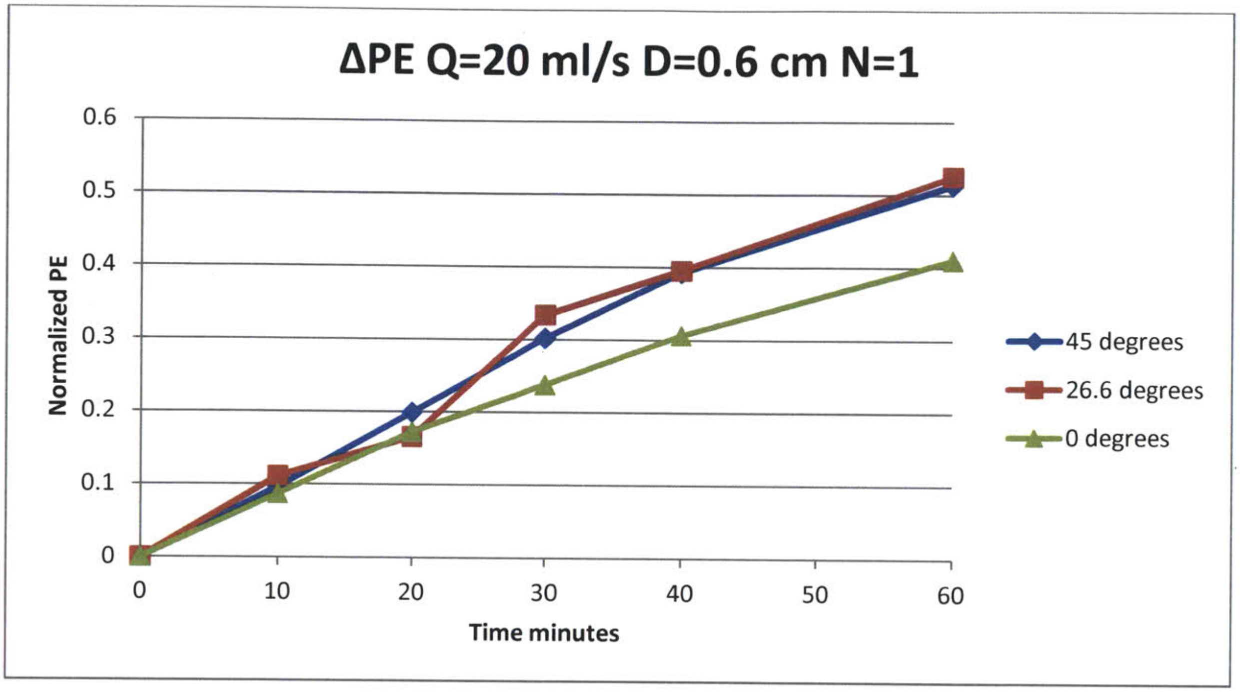

Figure 32. Normalized potential energy for Q=20, D=0.6 cm, and N=1

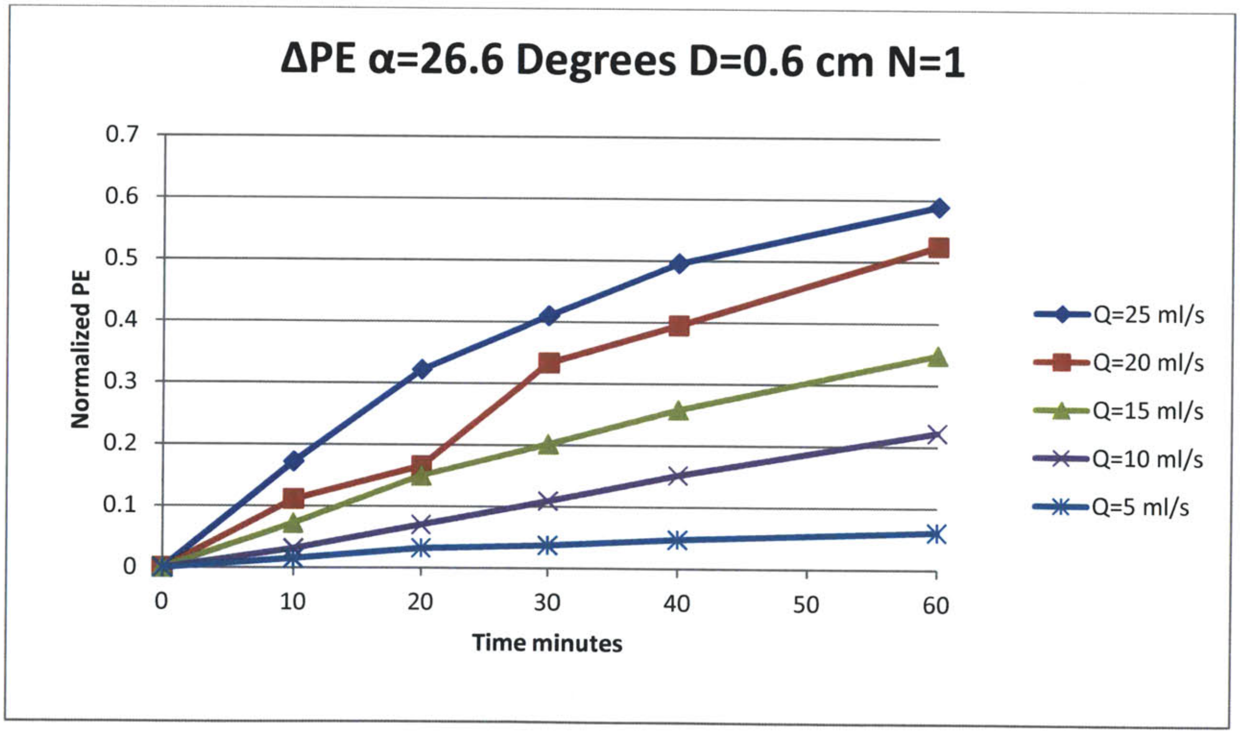

Figure 33. Normalized Potential Energy for α=26.6 degrees, D=0.6 cm, and N=1

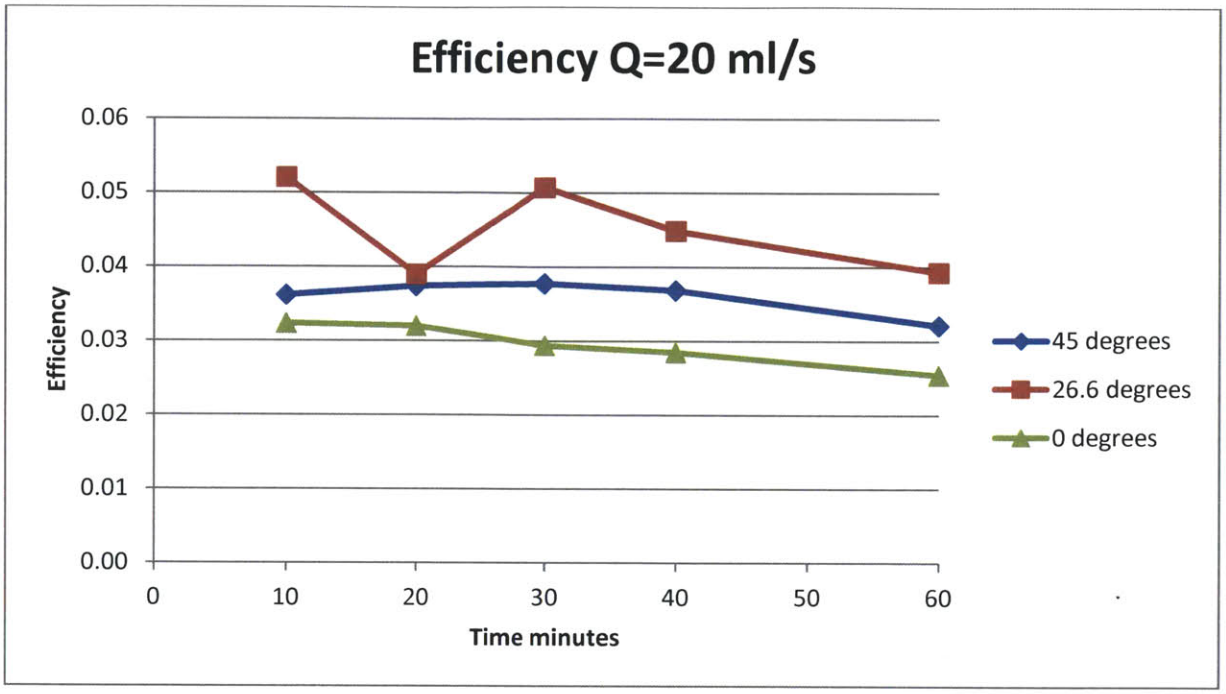

Figure 34. Efficiency at Q=20 ml/s, D=0.6 ml/s, and N=1

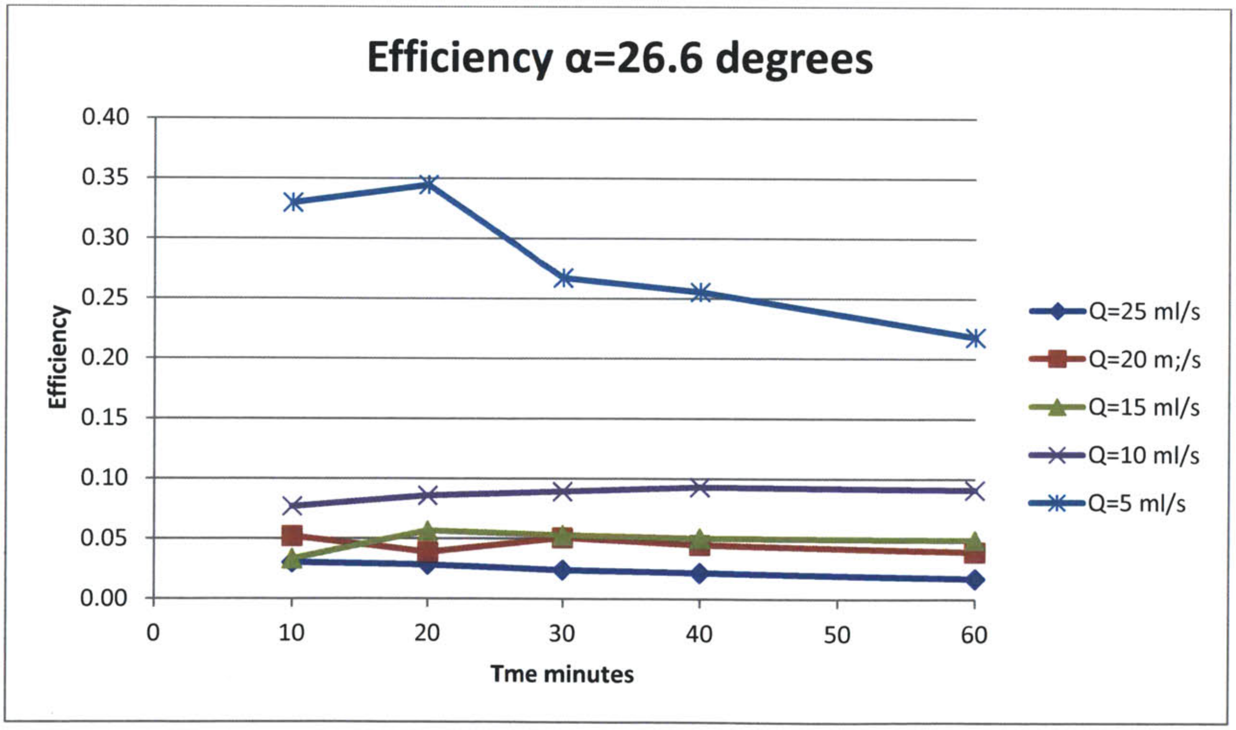

Figure 35. Efficiency at α=26.6 degrees, D=0.6 ml/s, and N=1

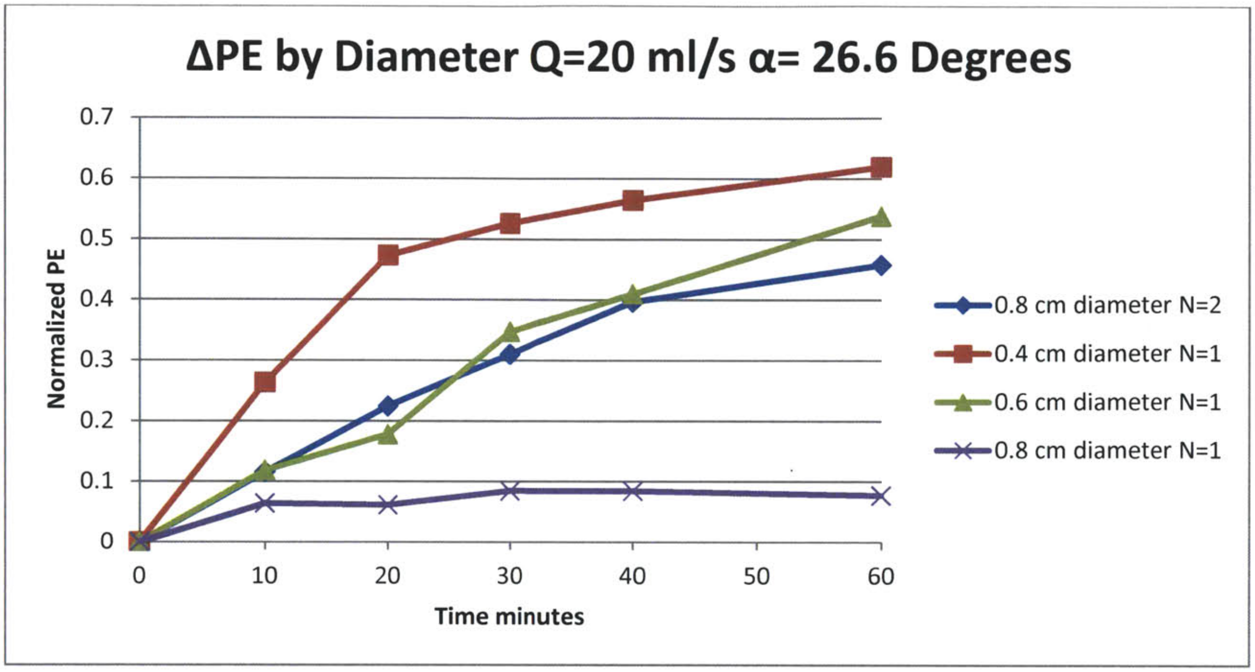

Figure 36. Change in Potential Energy by Diameter for Q=20 ml/s, α= 26.6 degrees

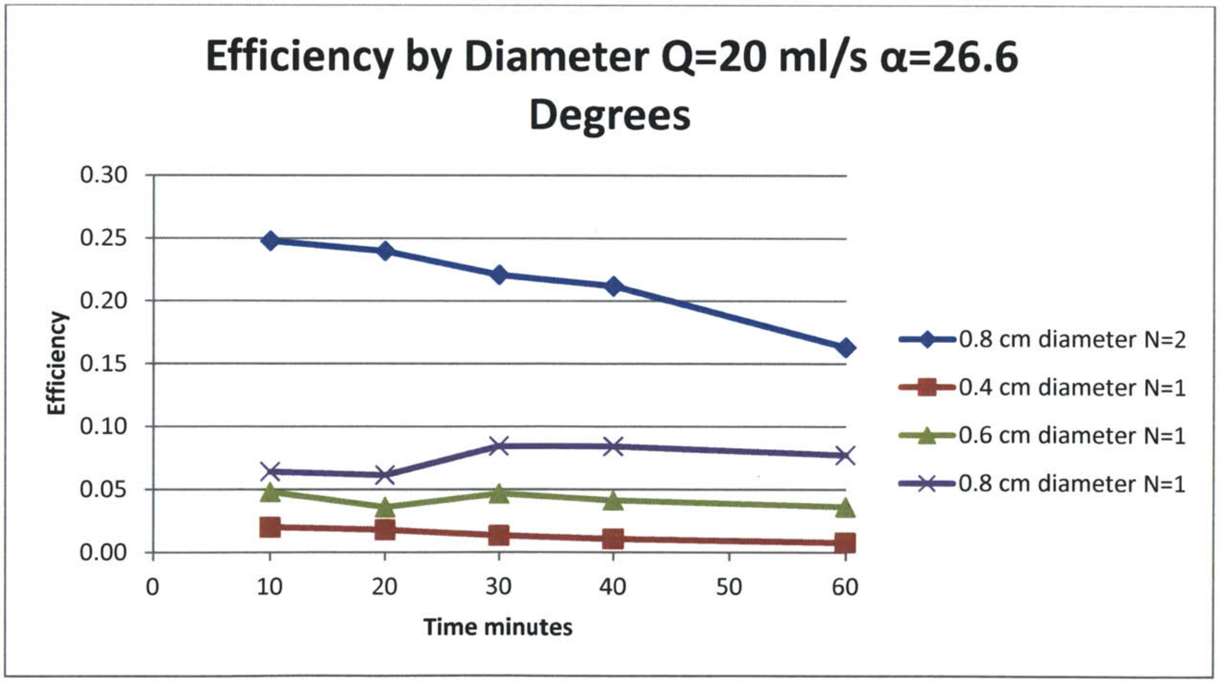

Figure 37. Change in Efficiency by Diameter for Q=20 ml/s, α= 26.6 degrees

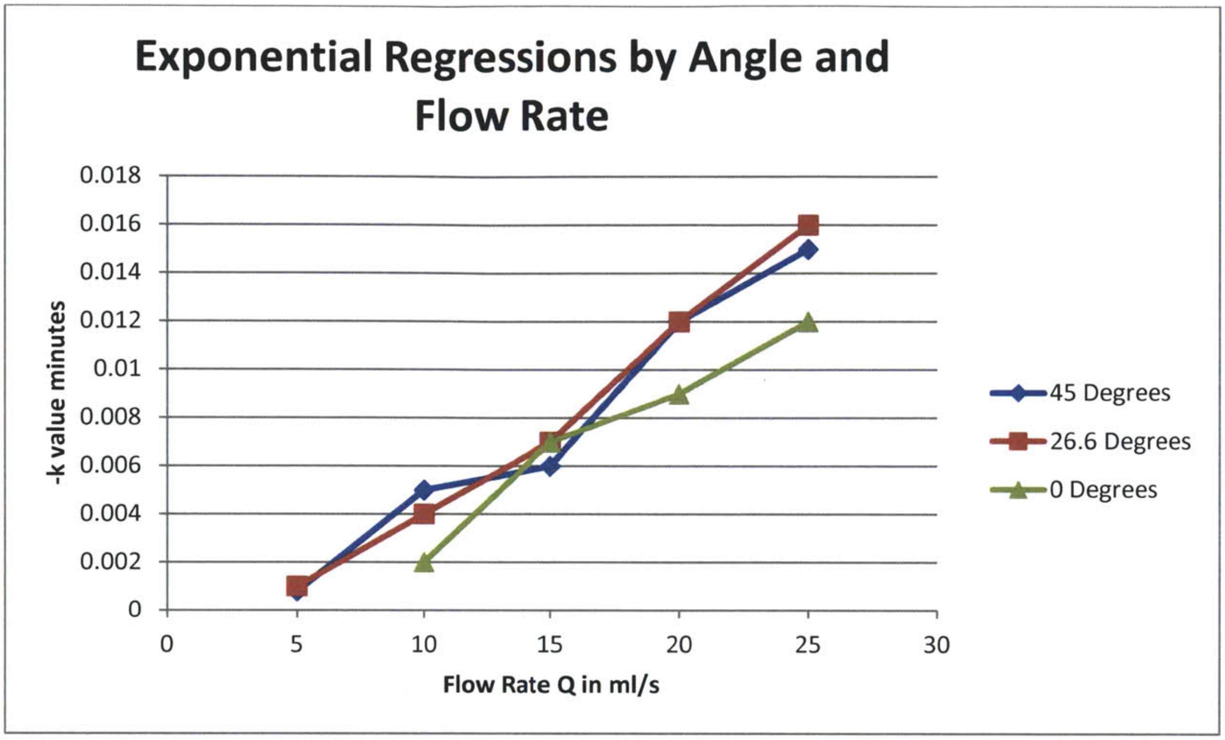

Figure 38. Exponential Regressions by Angle and Flow Rate.

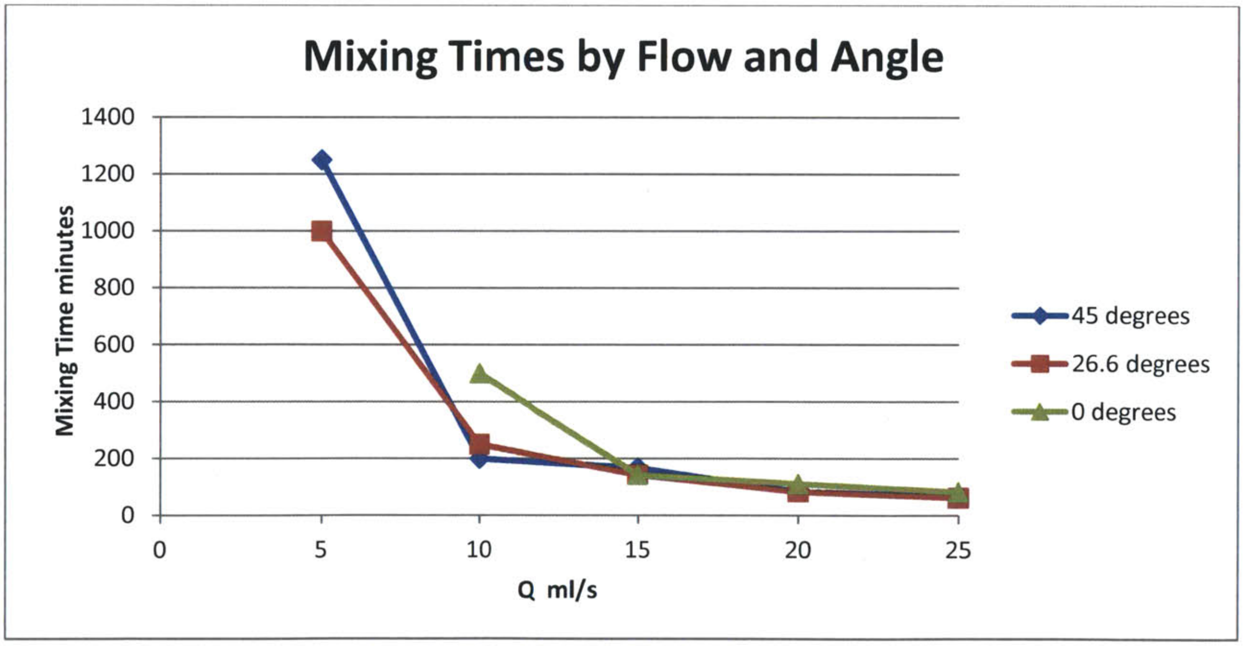

Figure 39. Mixing Times by Flow and Angle

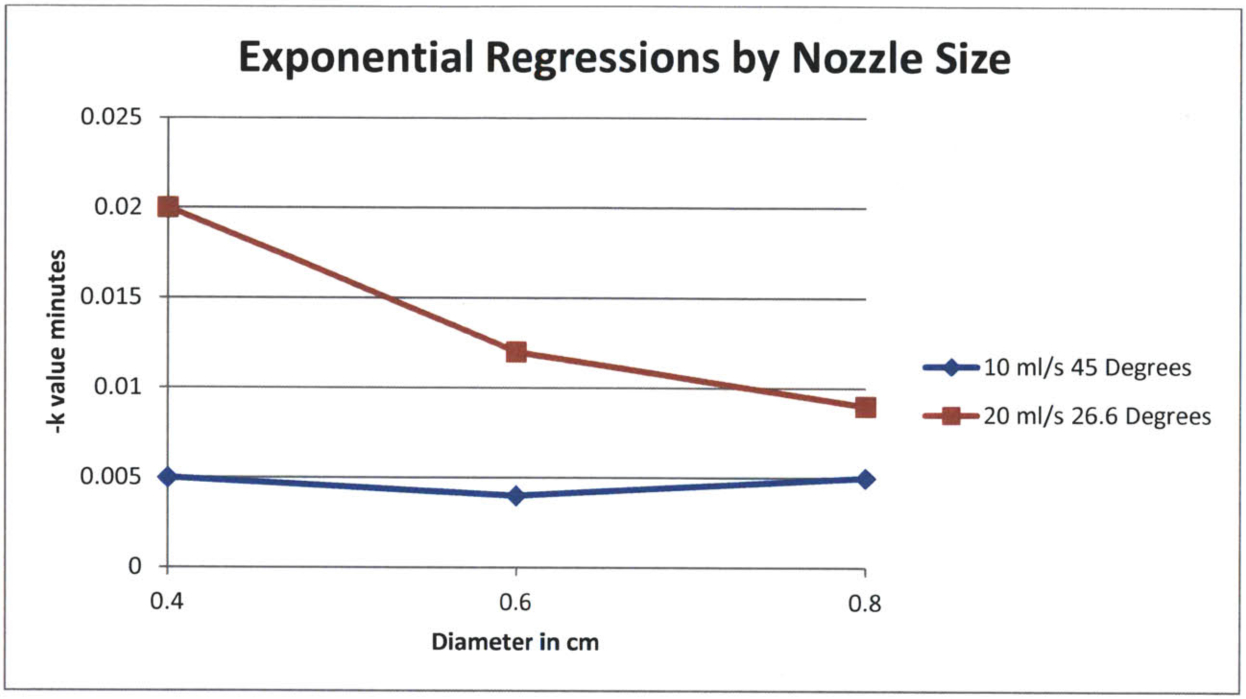

Figure 40. Exponential Regressions by Nozzle Size.

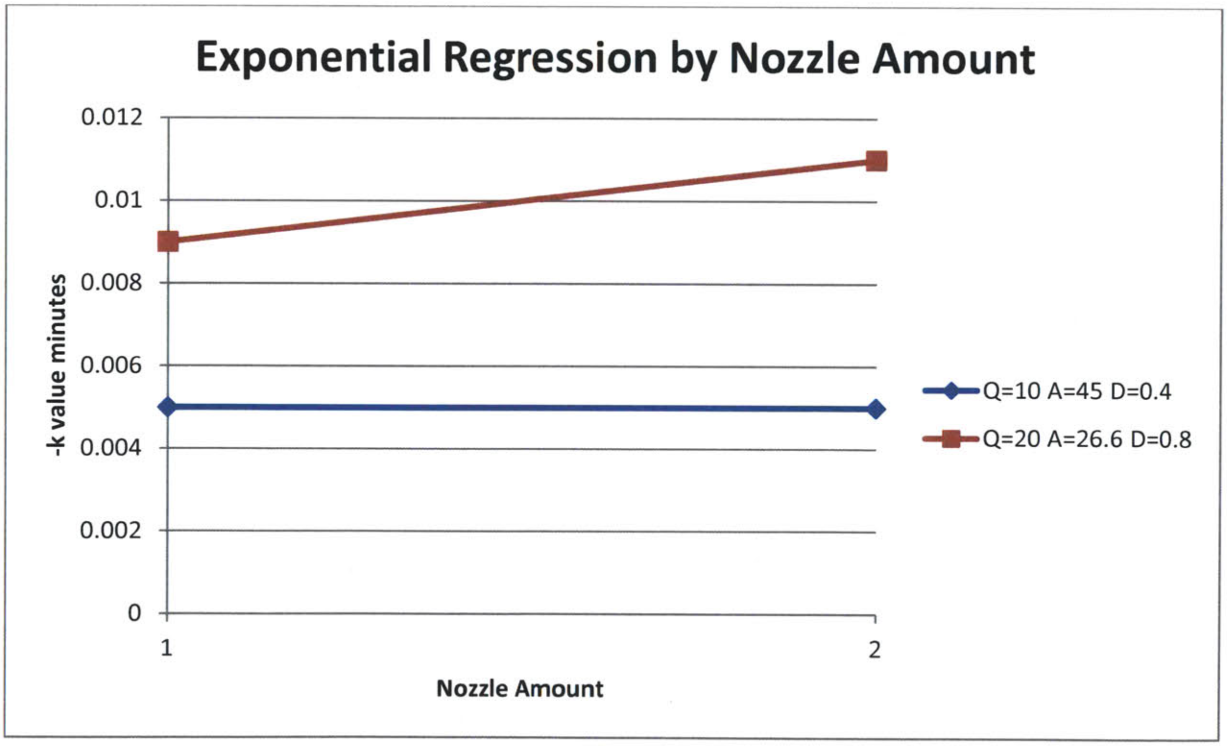

Figure 41. Exponential Regressions by Nozzle Amount.

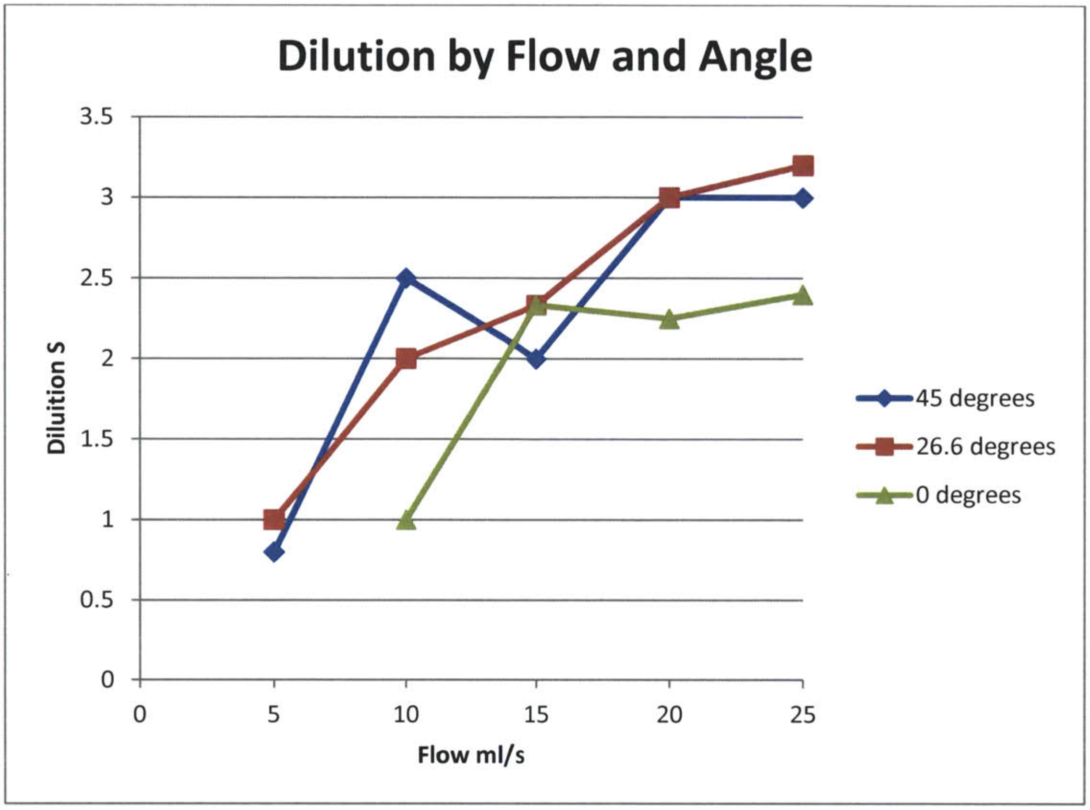

Figure 42. Dilutions by Flow and Angle

4. Application to the Charles River

4.1 Mixing times.

To determine the effectiveness of using turbulent jets that discharge from a bottom-based diffuser requires that we compare the mixing times of the different outflows. The results obtained from the experimental model can be related to the actual conditions of the Lower Charles River Basin. By establishing theoretical mixing times for the river, methods for mitigating the salinity intrusion can be implemented.

The amount of time it takes for a jet to mix with the water in the river is a combination of near field and far field mixing times. The time it takes the jets to mix the vertical water column is the near field mixing time. The time to fully mix the entire water body is the far field mixing time. The near field mixing times were determined by the experiment. The turbulent jets became less effective at mixing as time progressed resulting in an increase in near field mixing times. The best extrapolated mixing time for the model was slightly over an hour while the longest extrapolated mixing time was about 21 hours.

The far field mixing times are determined by the dimensions of the river and the river's flow rate. The Lower Charles River Basin behaves like a lake due to its large cross-sectional area. The velocity of the flow is low because the volume of the Lower Basin is large. The scaled model developed a circular flow pattern that recirculated the mixed water over the tank area and through the mixing jets. To relate the model mixing time to that of the Lower Basin, residence time had to be used instead of far field mixing times. The residence time is the amount of time required for a parcel of water entering a system to exit the other side. To calculate the residence time the quantity of the water flowing into the system is divided into the size of the system. The flow rate of the Charles River averages 368 cubic feet per second (Hall, 1986). The residence time of the Lower Basin can vary from a few days to 10 weeks (MADEP et. al., 2007) The lowest mixing times of the model were scaled to the Lower Basin using a time scale of T_r=6.2. The ~1 hour mixing time of the model scaled to a mixing time for the Lower Basin of ~39 hours ($T_{basin}=T_r*6.3$). The modeled mixing time of ~ 39 hours is less than the residence time of the Lower Basin which shows that using momentum jets to mix the Lower Basin is feasible. The jets can be used for a short period or run continuously and can be effective during both high and low flow periods.

The size of the salt wedge changes during the year. The saltwater gets partially flushed during the spring rainfalls. High momentum jets used during this period would take advantage of the lower residence times and increase the flushing. During the summer the saltwater builds up, reaching the maximum amount after the Fourth of July weekend. Some of this saltwater is pushed back into the harbor by the normal flow of the river. The salt wedge is at its smallest size during the winter as recreational boating use declines and the flow of storms flushes some of the salt out into the harbor.

This seasonality can be used to schedule removal of the salt wedge. Using a high flow for the momentum discharge, the excess salt from the Fourth of July weekend can be flushed into the harbor. A high discharge rate can be initiated in the spring to take advantage of the lowered residence times. Lower flow rates can be used to match the mixing times with the rate of saltwater encroachment from the harbor. The operation of the locks can be recorded and used to determine how much salt is entering the lower basin and when it is admitted. The momentum jets can be adjusted both in flow rate and in length of operation to match the number of lock cycles used. Adjustments for leakage through the dam can be determined and implemented when the known amount of salt entering through the locks is calculated and recorded.

The Charles River watershed takes a about week to drain into the Lower Basin. The flow rates for the Lower Charles River Basin can be accurately forecasted according to the precipitation upstream. This allows the mixing discharges to be matched with the river flows. Seasonal fluctuations in rainfall can be coordinated with the seasonality of the salinity encroachment to coordinate the discharge rates.

The best way to use turbulent jets to keep the salt wedge from intruding into the Lower Basin would be provide a high flow discharge to flush the basin after the Fourth of July weekend and then periodic low flow discharges coordinated with high river flows. A permanent low flow discharge would keep the salt wedge from establishing itself in the lower basin.

4.2 Comparison to bubblers

In 1979 a bubbler system was installed to remove salt that had intruded into the Lower Charles River Basin. Five bubblers were placed along the bottom of the river. The bubbles then entrained the surrounding water drawing it to the surface much like the turbulent jets studied here. This brought the heavier salt water to the top layers of the water column and then the river flow flushed the saltwater out to the harbor. Comparing the water quality tests before the bubblers were installed in 1979 to tests run after the bubblers had been working for a year and a half showed their success in removing most of the saltwater. The stratification gradient was reduced and bottom salinity levels were lowered substantially. This resulted in the DO (dissolved oxygen) levels being higher throughout water column.

The proposed bottom-based diffuser discharge would provide an outflow of 35 MGD spread over 15 outlets spaced about 3 meters apart. This would be installed in a location close to the northern bank of the river. The results of my experimental model show that this arrangement would fully mix the Lower Charles River Basin over a period of several days. Like the bubblers, the diffuser would not necessarily mix the bottom layers. However the diffuser has been designed with adjustable discharge angles which could allow for mixing the bottom layers or scouring the bottom sediments.

The bubblers mix the water by entraining the surrounding water into the upward flow of the bubbles. The bubbles are discharged from a pipe along the river bottom and then disperse upwards forming a narrow vertical cone. This entrainment is limited by determined by the flow rate of the bubbles and the discharge arrangements on the outflow pipe. Because bubbles are a source of buoyancy (B), the plume flow rate (Q) increases with height (z) as

$Q \sim B^{1/3} z^{5/3}$,

meaning more of the entrainment occurs at higher elevations within the column where mixing is less effective. By contrast, turbulent jets work mainly by momentum (M) so induce a flow that varies with distance along the trajectory (x) as

$Q \sim M^{1/2} x$.

Operating the bubblers requires energy mainly to compress the air to the pressure at the bottom of the river. This power can be shown to be

$Power_{bubbler} = P_{air}*Q_{air}*\ln[(H+H_{air})/H]$

where, for each of the former Charles River bubblers

P_{air} = Air pressure in Pa

$Q_{air} = 0.07\ m^3/s$

$H = 9$ m

which yields 4.7 in kW (CDM, 1976).

The diffuser requires needs power to provide the kinetic energy associated with the flow rate and velocity. Assuming a total flow rate Q through N nozzles of diameter D_o, this power is

$Power_{diffuser} = 0.81*\rho*Q_o^3/(N^2*D_o^4)$

For $Q_o = 1.8\ m^3/s$, $N = 15$ and $D_o = 0.23$ m, this yields 7.9 kW.

Five bubblers were used which resulted in the total energy cost being three times more than the diffuser and while a comparison between field measurements (bubblers) and lab measurements (diffusers) is not completely fair, it appears that the diffuser is more effective.

Funding the bubblers was the responsibility of the MDC. This agency is responsible for

450,000 acres of parks and some of the most historical sites in our country. Unfortunately the water quality at the bottom of the Lower Charles River Basin was not always a priority and the funding for the bubblers was ended in 1981.

If the diffuser had been included in the EPA's 2011 NPDES permit, which it was not, the energy needed for the diffuser discharge would now be provided by Kendall Station. Likewise the plant would also pay for the installation and maintenance of the diffuser. The company would keep the diffuser in good working order because its operation would be directly related to the company's profit.

Several alternative methods are available to remove some of the saltwater from the Lower Charles River Basin. Placing bubblers by the dam where the salinity gradient is highest could be an effective method to keep the salt from encroaching up the river. Movable bubblers could be implemented allowing larger areas to be covered. Further studies on the effectiveness of the bubblers would allow them to be used more efficiently, running only when the Lower Basin residence times were short, to take advantage of the flushing. The bubblers could be run in relation to the use of the locks. Maintaining a bubbler system could be a condition of the Kendall Station's discharge permit. Either bubblers or bottom discharge jets or both would be required to mitigate the anoxic layer on the Charles River bottom. I believe it would be better to use the resources available from the Kendall Station to mitigate the saltwater than to depend upon the politics of local communities or government agencies.

4.3 Other considerations

Blue-green algae is a major concern to the EPA regarding using a diffuser for the discharge from Kendall Station. Blue-green algae is the common term used to describe cyanobacteria. This bacteria uses light for photosynthesis. Under the right conditions the bacteria rapidly reproduce creating a "bloom" which covers portions of the water's surface with mats of algae. These conditions are warmth, residence time (slow moving water), and nutrients (mainly phosphorus). These conditions have been occurring with greater frequency in the Charles River as the average temperatures increase and fertilizer runoff increases from continued residential growth.

Several of these cyanobacteria produce toxic chemicals. When this occurs in conjunction with a "bloom", the natural organisms of the river die off. When the "blooms" use up all the nutrients in the river the bacteria die and their decomposition reduces the dissolved oxygen levels in the river. The algae are a major concern, as the Charles River is a central recreation point for the City of Boston. Floating mats of blue-green algae and the resulting decaying mats would degrade the beauty of the river. Recently blue-green algae has been seen in the Lower Basin. This has occurred when the conditions of low river flow (long resident times) and hot ambient temperatures have been maintained for at least a week.

An objection to the proposed diffuser is that discharging the heated water at the bottom of the river would promote these blue-green algae blooms. However a bottom discharge would mix with the cooler, bottom water, resulting in slightly lower surface temperatures. Currently the heated discharge is released at the surface where the photosynthetic cyanobacteria grow. The Lower Charles River Basin is relatively shallow in relation to its width. Its flow rate is diminished during the summer months. The limiting factor for the blue-green algae blooms is the lack of the nutrient phosphorus. The incidents of blue-green algae in the Charles River have all occurred when the phosphorus levels were high. This happens when the region experiences a period of heavy rainfall followed by a long hot spell. The heavy rains flush the fertilizer from the lawns, playing fields, and farms upstream. It takes a week or more for the nutrients to make it down to the Basin from the watershed and in that time the ambient temperatures might rise. To mitigate this, the amount of phosphorus washed into the river needs to be reduced. The EPA suggests that upstream communities reduce fertilizer runoff as a solution. The CSOs (combined sewer outflows) dumping into the river have almost all been eliminated and hopefully the remainder will be removed soon. There is a concern that the momentum jets would bring phosphorous from the bottom to the river's surface, promoting the algae blooms. By breaking up the stratification of the saltwater, the jets would bring dissolved oxygen to the bottom of the river. This DO would allow cause the iron oxides in the sediments to bind with the phosphorous, reducing the phosphorous in the water column. Therefore a fully mixed river would reduce the chances of blue-green algae formation since the iron oxides would reduce the phosphorous.

Another concern of installing the diffuser is bottom scouring. This is the removal of the sediments on the river bottom by the jets' flows. My experiment showed that with an outflow placed five feet above the bottom, the density gradient of saltwater was great enough to inhibit mixing of the bottom layer. This layer was mixed slightly when the discharge angle was set to 0°

The Charles River has been used for disposing of wastes since the land was colonized in the 1600's. When the industrial age began the river was a prime location for manufacturing. A tremendous amount of varied chemicals were disposed of in the river before it was determined that they were health hazards. Many toxic chemicals are embedded in the sediments under the river. The polluting has been gradually phased out since the Clean Water Act in 1970 set about to clean the nation's waterways. The river has been healing ever since, but toxic chemicals still remain in the sediments.

The polluted sediments remain a detrimental factor to the health of the river. They compromise the benthic (bottom) ecosystem of the river. Many types of aquatic life use the river bottom at some point in their life cycle. The polluted sediments and the anoxic layer inhibit this life in the Charles River. Momentum jets could be used to scour the river bottom of the contaminated sediments. This could be done by rotating the discharge jets to their lowest angle and using their maximum flow in conjunction with a high flow river event to flush the sediments out of the river. Mitigation of the wastes could be focused at the points where the water flows through the dams. The scouring could be scheduled to have the least environmental impact, by being done when there are no fish migrations or spawning and when the flow rate of the river is high. To adhere to the Clean Water Act's mandate of making the Charles River "fishable and swimmable", something has to be done about the sediments. A bottom based diffuser offers a unique opportunity to remove them.

5 Conclusions

The results of the experiments show that placing momentum jets at the bottom of the Lower Charles River Basin can mitigate the saltwater intrusion from the Boston Harbor. The experimental model showed that, with the better nozzle configurations, it takes roughly 1 hours to remove the salinity stratification in the model, which scales to about 2 days for the Lower Basin between the Longfellow and Cragie bridges.

Momentum jets were tested at the following flow rates: 5,10,15,20 and 25 ml/s. The results of the experimental tests showed that the effectiveness of the mixing was directly related to the flow rate with the highest flow rate of 25 ml/s being the most effective. The momentum jets were set at three different angles: 0°, 26.6°, and 45°. The lowest angle (0°) was least efficient as the energy was used to push the water around the tank instead of mixing. The highest angle (45°) also had a lower efficiency as the jet's energy was wasted, reflecting off the surface of the water. The middle angle used (26.6°) had the best efficiency.

Bubblers have historically been used for destratification, and could be used again, though analysis shows them to be somewhat less efficient than momentum jets. Even so, they would be effective if run 40-50 days out of the year.

The mixing provided by the momentum jets will increase the amounts of dissolved oxygen in the water column. This DO will help the iron oxides to bind with the phosphorous. Reducing the phosphorous levels in this manner will lower the possibilities of blue-green algae blooms in the Lower Basin

There is a great deal of flexibility in implementing momentum jets since the experimental results of 39 hours to remove the salinity stratification for a portion of the Lower Charles River Basin is much smaller than the one year that the salinity intrusion takes to establish itself. Only by instituting a method of mixing and flushing the saltwater out of the Lower Basin can the Charles River reach the standards set by the Federal Clean Water Act of being “fishable and swimmable”.

To accomplish this, I would recommend using high flow momentum jets to flush the river in conjunction with the first major rainfall after the Fourth of July celebration. A slower flowing jet would be run intermittently throughout the year to keep the saltwater from reestablishing itself. When the salinity reached specific levels or when the locks had been used a certain amount of times, high flow jets would be used to flush the access saltwater from the Lower Basin.

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