Spatial Distribution, Temporal Variability, and Chemistry of the Salt Wedge in the Lower Charles River, Massachusetts, June 1998 to July 1999

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INTRODUCTION

The Charles River is of great recreational and ecological value to the Boston metropolitan region and the Commonwealth of Massachusetts. It is also the focus of the U.S. Environmental Protection Agency (USEPA) Region I, Clean Charles 2005 Task Force. The main goal of the Task Force is to make the Charles River “fishable and swimmable” by the year 2005. Achieving “fishable and swimmable” conditions will require continued progress in addressing a range of environmental conditions now degrading water quality, including the infiltration of saltwater from Boston Harbor into the freshwater Charles River.

To better understand the pattern of saltwater intrusion, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), Massachusetts Department of Environmental Management (MADEM), and New England Interstate Water Pollution Control Commission (NEIWPCC), collected data on the spatial distribution, temporal variability, and chemistry of the saltwater that entered the lower Charles River from June 1998 to July 1999. The purpose of this investigation is to extend and complement a regional-scale study of Charles River water quality conducted in 1996 (T. Faber, U.S. Environmental Protection Agency, written commun., 1997), and the ongoing water monitoring activities of the Massachusetts Water Resources Authority (MWRA) and the Charles River Watershed Association (CRWA). The data collected by this investigation supports the Clean Charles 2005 Task Force by providing detailed information concerning a major factor limiting “fishable and swimmable” conditions in the lower Charles River. Finally, the study will be used to assist current planning efforts of the Metropolitan District Commission (MDC) to restore the historic parklands of the lower Charles River.

The “Basin” is the local term for the reach of the Charles River that begins at the Watertown Dam in Watertown, Mass., and extends about 8 mi through suburban and urban areas to Boston Harbor. Discharge to the harbor is controlled by the “new” Charles River Dam in Boston (fig. 1). The Basin was created by construction of the “old” Charles River Dam in 1908 to solve Boston’s sanitary problems. Prior to the building of the old Charles River Dam, the lower Charles River was a tidal estuary in which the water levels rose and fell twice daily with the tidal cycle. Low tide would expose untreated sewage that was discharged directly into the river. Exposed sewage created noxious odors and served as a breeding ground for mosquitoes that caused sporadic epidemics of malaria and yellow fever (Jobin, 1998). Damming of the river interrupted the normal tidal cycle and flooded the estuary by creating a freshwater pool (the Basin) that had a constant water elevation of about 0.8 meters (m) above mean sea level. Flooding of the estuary initially improved sanitary conditions and the Basin became a source of enjoyment for the local population and the focus of a large waterfront park in Boston and Cambridge (Jobin, 1998).

Although the infiltration of saltwater from the harbor into the Basin was anticipated when the old Charles River Dam was built, neither the magnitude nor the consequences of the infiltration was considered. By 1975, the Metropolitan District Commission (MDC) determined that harbor water covered about 80 percent of the river bottom within the Basin and composed about 50 percent of its depth. The MDC also concluded that fish kills and odors in the spring of 1975 were likely the result of the sulfide-rich saltwater mixing with the overlying freshwater (Metropolitan District Commission, 1975).

Saltwater from Boston Harbor that enters the Basin is known as the “salt wedge” because of the shape it assumes as it moves upstream. Freshwater discharge from upstream pushes against the intruding harbor water until the density differences cause stratification to occur; the freshwater then overrides the denser harbor water (Fischer and others, 1979). The depth from the river surface to the top of the salt wedge is directly related to the force of the upstream flow and inversely related to the difference in density between the freshwater in the Basin and the harbor water. As the freshwater flows over the harbor water, shear stress develops at the freshwater-saltwater interface, which causes the upper surface of the salt wedge to form a slope that reflects the dynamic equilibrium between freshwater discharge and saltwater intrusion.

The “new” Charles River Dam was built in the late 1970s as a replacement for the old dam. Features that were meant to significantly reduce saltwater intrusion of harbor water into the Basin were incorporated in the design of the new dam, and reductions of harbor-water intrusion by as much as 80 percent were predicted (Metropolitan District Commission, 1975). Special features of the new dam included small locks with tight seals and two sluice gates. One of the sluice gates is 6 m below the water surface and was designed to drain the salt wedge at low tide. Six large pumps control the water level in the Basin during flooding, and could be used to pump the salt wedge out of the Basin. Each of these pumps is capable of pumping about 40 cubic meters per second (m^3/sec) of water from the Basin into Boston Harbor.

Although the new dam was designed to reduce the infiltration of harbor water into the Basin, its present-day operation results in large volumes of harbor water entering into the Basin, particularly during times of high-recreational boating use. When the gates of the locks are opened to allow boats into or out of the Basin, freshwater flows out of the Basin over the same volume of harbor water infiltrating the Basin. It has been estimated that about half of the volume of water in the lock enters the Basin during each lock cycle (a lock cycle is composed of two lock openings—one for a boat entering the basin and one for a boat exiting the basin). There are three locks at the new dam: two small locks (61.0 m x 7.6 m) and one large lock (91.4 m x 12.2 m). Assuming that each lock is used for one-third of the lock cycles and given that the observed average height of water is 3.4 m in the small locks and 4.6 m in the large lock, about 136.7 cubic meters (m^3) of harbor water enters into the Basin per lock cycle.

The presence of the salt wedge can have profound effects on geochemical conditions within the Basin including: (1) increased salinity, (2) decreased oxygen concentrations, (3) increased production of hydrogen sulfide, (4) sequestration and immobilization of trace metals, and (5) increased internal loading of nutrients, such as phosphorus. All of these changes affect organisms that live within or pass through the Basin, especially benthic organisms and fish.

STUDY METHODS

Water-quality surveys were conducted weekly, bi-monthly, and monthly to determine the seasonal variability in the extent and chemistry of the salt wedge in the Basin (fig. 1). Water-quality profiling locations were determined using channel morphology as a guide; these locations were primarily along the deepest parts of the Basin because the density of the saltwater causes it to sink to the bottom and reside in the deepest part of the channel.

Channel morphology was mapped from water depths interpreted from video recordings of echo sounder output and a portable, high-precision global positioning system (GPS). Data was processed using the triangular irregular network (TIN) data model (Environmental Science Research Institute, Inc., 1997) (fig. 1).

Field measurements of water depth, specific conductance, salinity, pH, temperature, dissolved oxygen, turbidity, and oxidation-reduction potential (redox) were made with a Hydrolab instrument at 1-m intervals from the water surface to the river bottom at each water-quality profiling location. To minimize data collection error, the Hydrolab was calibrated at the beginning of the sampling day and its calibration was checked at the end of the day to determine if the Hydrolab readings had drifted outside the instrument specifications (Hydrolab, 1996). Analysis of post-calibration data indicate that the Hydrolab operated within acceptable limits for all of the water-quality surveys.

Salinity measurements that were greater than 0.5 parts per thousand (ppt) at each of the water-quality sampling sites were entered into an Arc Macro Language (AML) program (Environmental Science Research Institute, Inc., 1997). Salinity is the sum of the concentrations of major ions in seawater and includes chloride, sodium, sulfate, magnesium, calcium, potassium, bicarbonate, bromide, boric acid, strontium, and fluoride (Ingmanson and Wallace, 1989). Salinity values between water-quality sampling sites were estimated using GRID commands (a module of ARC/INFO) within the AML. Volumes of the salt wedge and salt mass were calculated with the AML for 1-m depth intervals. Total volume of the salt wedge and mass of salt in the Basin were calculated as the sum of the volumes and salt mass calculated for each 1 m of the water-column.

SPATIAL DISTRIBUTION AND TEMPORAL VARIABILITY OF THE SALT WEDGE

Because the density of the harbor water causes it to sink to the bottom of the channel, its spatial distribution is dependent not only on the amount of harbor water infiltrating into and discharging from the Basin, but also upon the channel morphology of the Basin. The present-day channel morphology of the Basin is similar to that of the original tidal channel and associated mudflats surveyed in detail prior to construction of the old dam (Pritchett and others, 1901); however, the bathymetry of the Basin surveyed in 1901 has been slightly modified by sediment accumulation and man-made holes dug during the last 97 years. The denser harbor water that infiltrates the Basin generally collects in these holes (fig. 1).

Other important morphological features of the Basin that affect the distribution of the salt wedge are berms beneath the Longfellow and Harvard Bridges (fig. 1). These berms are only about 4.6 m below the water surface at some spots, and they deter the movement of the salt wedge upstream, because the salt wedge must fill the downstream part of the Basin to a level greater than the height of the berm before it can spill over the berm and move upstream.

Several other factors control the distribution and temporal variability of the salt wedge, including freshwater discharge of the Charles River; number of lock cycles; pumping; and opening and closing of the lock gates, culverts, sluice gates, and the fish ladder. These factors vary seasonally and with the weather. For example, during the summer months boat traffic is heavy. The increased boat traffic allows more harbor water to infiltrate into the Basin through opening of the locks than in the winter, when the locks are seldom used. Also, freshwater discharge from upstream is generally lowest during the summer and highest in the winter and spring. The increased discharge in the winter and spring increases the resistance of freshwater to harbor-water movement upstream into the Basin. Finally, lock gates, culverts, and sluice gates also are open more frequently during times of increased discharge to prevent flooding.

In addition to seasonal effects, storms can occur at any time during the year, resulting in rapidly increasing freshwater discharge due to the large amount of impervious surface in the watershed. In order to prevent flooding during storms, the dam operator will use pumps or open the lock gates, or both, to move water from the Basin into Boston Harbor. Pumping at depth and opening the lock gates at low tide, in combination with the increased discharge from upstream, can flush the salt wedge completely out of the Basin. Tables 1 and 2 list the summary statistics for some of these factors recorded during the study period.

Just prior to the first water-quality survey of this study, the Charles River drainage basin received more than 20 cm of rain as the result of an intense, slow-moving storm. This storm, which occurred June 12 to 15, 1998, resulted in a peak flow of more than 62.0 m^3/s at USGS gaging station 01104500 on the Charles River at Waltham, Mass., and equalled the 13-year flood for this station. A flow of this magnitude at this station has an estimated recurrence interval of 13 years (Parker and others, 1998), which means that the flow would be expected to be equaled or exceeded once in 13 years. In addition to water discharged into the Basin from upstream, it is likely that discharge from numerous storm drains and combined sewer overflows during intense storm events, doubles the volume of water entering the Basin (M. Roberts, Charles River Watershed Association, oral commun., 1998). During the June storm, the dam operator at the new dam pumped about 19.0 x 10^6 m^3 of water out of the Basin and opened the locks to allow water to flow out of the Basin into Boston Harbor, in order to prevent flooding. The combined effect of the high discharge from upstream, the pumping of water at depth out of the Basin, and the opening of the locks appears to have completely flushed the salt wedge out of the Basin by June 15.

During the four-day period following this storm, the salt wedge formed again in the Basin. By June 19, the wedge was detected at a depth of 6 m at the new dam locks, and at a depth of 8 m below the commuter rail draw bridge (fig. 1). The salt wedge advanced despite relatively high average daily mean discharge (estimated at 60 m^3/s; table 1) and continual pumping at the new dam (at an average rate of 5.5 x 10^6 m^3/day; table 2). During the next five days (June 20–24), daily mean discharge averaged 49 m^3/s and pumping at the new dam averaged 3.3 x 10^6 m^3/day. Nevertheless, the salt wedge continued to move upstream and began to fill the area just upstream of the old dam near the Museum of Science. The lock at the old dam, which is always left open, is an important control point for the movement of the salt wedge upstream because the salt wedge must pass through the lock, and most of the freshwater moving downstream also must pass through the narrow lock at the old dam, thereby increasing the force opposing the movement of the salt wedge upstream compared to other areas of the river. Therefore, the density of the salt wedge must increase to a point at which it can overcome this force before moving through the locks and into the main part of the Basin.

A second storm of lesser intensity occurred on June 25. During this storm, the lock gates on the new dam were opened for more than 12 hours during low tide, and 13 x 10^6 m^3 of water was pumped from the Basin at depth to prevent flooding. By July 1, 1998, the combined effects of increased discharge, pumping at depth, and lock openings (during low tide) almost completely flushed the salt wedge out of the Basin for a second time.

More than 500,000 people attend the Fourth of July celebration on the banks of the lower Charles River to watch fireworks and listen to the Boston Pops Orchestra. Many of those attending come by boat from Boston Harbor; from July 1 through 15, 1998, 5,441 boats entered and exited the Basin. About 728 lock cycles, lasting an average of 10 minutes per cycle, were needed to convey this number of boats into and out of the Basin (an average of 52 lock cycles per day). Hence, the locks were open 120 hrs during the 15 days between water-quality surveys (on July 1 and 15, 1998). In addition, the average daily mean discharge of the Charles River during this period had decreased to about 23 m^3/s. The salt wedge on July 15 had moved upstream from the old dam, increasing the salt mass in the Basin by 1.2 x 10^6 kilograms (kg) in 14 days, or 0.08 x 10^6 kg/day (table 3).

Although the boat traffic is greatest during the Fourth of July celebration, traffic remains heavy for the rest of the summer. For example, lock cycles averaged 39 per day during the period July 15 to August 19; 6,777 boats entered the Basin in 35 days, requiring 1,381 lock cycles. In addition, the average daily mean discharge of the Charles River during this period dropped to less than 7.0 m^3/s and only about 1.2 x 10^6 m^3 of water was pumped from the Basin into Boston Harbor. The combined effects of the large number of lock cycles, reduced upstream flow, and reduced pumping resulted in the advance of the salt wedge to the vicinity of the Harvard Bridge by August 19.

August 19, 1998, marked the first time anoxic conditions were measured in the Basin during the sampling period. Concentrations of dissolved oxygen (DO) were less than 1.0 milligrams per liter (mg/L) at stations 3.5-A, 3.5-B, and 3.7-A (fig. 1) at a depth of about 6 m. Anoxic conditions develop in the salt wedge due to oxygen uptake by heterotrophic bacteria in the sediment and the slow transfer of oxygen from the overlying freshwater to the salt wedge. Anoxia in the Basin is important not only because aerobic organisms cannot survive in oxygen-deficient environments, but because naturally occurring sulfate in the salt wedge is quickly converted to hydrogen sulfide (H_2S) under anoxic conditions. Hydrogen sulfide is extremely toxic to aerobic organisms because it inactivates the enzyme cytochrome oxidase, interfering with energy metabolism at the cellular level (Cole, 1975).

The average daily mean discharge from the Basin into Boston Harbor over the next 49 days (August 19 through October 7) was the lowest average discharge measured in 1998 (5.7 m^3/s) and, although there were fewer than 25 lock cycles per day, by October 7 the salt wedge had advanced to just downstream of Harvard Bridge, and reached its maximum volume (2.6 x 10^6 m^3) for 1998. In addition, much of the area occupied by the salt wedge below a depth of 6 m had become anoxic.

The average daily mean discharge between October 7, 1998 and November 17, 1998, more than doubled from 3.3 m^3/s to 8.5 m^3/s; however, even the force of this increased flow was not sufficient to flush the salt wedge out of the Basin because of the large amounts of harbor water that entered the Basin (0.009 x 10^6 m^3/day) during lock cycles. Consequently, the net salt mass in the Basin during this period increased from 12 x 10^6 kg to 15 x 10^6 kg, which was the maximum salt mass measured in the Basin for 1998. It is important to note that the spatial extent and the salt wedge and the salt mass in the Basin in 1998 was probably considerably less than average because of the flushing of the salt wedge by runoff from the June storm.

Between November 17, 1998, and March 17, 1999, lock cycles averaged fewer than two per day, resulting in very little harbor water infiltrating into the Basin. During the same period, the daily mean discharge of the Charles River generally increased. As a result, the upstream advance of the salt wedge ceased, and the salt mass in the wedge declined. The decline in salt mass was probably due to entrainment and export of saltwater caused by increased freshwater flow, in conjunction with reduced salt input from Boston Harbor during this period. Although the daily mean discharge generally decreased from March 17 to May 6, 1999, the salt mass in the Basin continued to decline, again likely due to the low number of lock cycles (about 5 lock cycles per day).

May 26, 1999, was the last day of measurable rain in the Boston area for 31 days and was the beginning of a period of drought (R.S. Socolow, U.S. Geological Survey, oral commun., 1999). The daily mean discharge of the Charles River fell from 15 m^3/s on May 26 to less than 1.6 m^3/s by June 26. Freshwater flow in the river offered little resistance to the advance of the salt wedge upstream. By June 4, most of the Basin downstream of the Longfellow Bridge at depths greater than 5 m was occupied by the salt wedge, and the salt mass in the Basin increased by 0.48 x 10^6 kg.

Water-quality measurements recorded on June 4, 1999, between the Museum of Science and Longfellow Bridge showed that most of the water column at depths greater than 6 m had become anoxic. It is likely that the water in the area between the new dam and the Museum of Science does not become anoxic because this area is frequently replenished with oxygenated harbor water. In addition, the water also became anoxic at depths greater than 6 m upstream of the Longfellow Bridge due to thermal stratification and hypolimnetic oxygen demand during this period. Decay of organic matter rapidly consumes dissolved oxygen under conditions of thermal stratification; however, photosynthetic dissolved oxygen production by phytoplankton in the epilimnion likely prevents the entire water column from becoming anoxic.

By June 18, 1999, the salt wedge filled the Basin downstream of Longfellow Bridge to the extent that it spilled over the berm beneath the bridge and into the first deep hole located upstream of the bridge (fig. 2). By June 18, the thermal stratification of the Basin was apparently disrupted, probably due to wind, and much of the Basin upstream of Longfellow Bridge was aerobic, except for the deep hole just upstream of the bridge that recently had filled with harbor water. The salt wedge area between Longfellow Bridge and the Museum of Science remained anoxic as it was not mixed by wind forcing. By June 23, the salt wedge filled much of the Basin between the Longfellow and Harvard Bridges below a depth of 5 m. From June 18 to June 23, the salt mass in the Basin increased by 3.3 x 10^6 kg. No oxygen data were collected during the June 23 water-quality survey.

By June 29, the salt wedge filled in much of the Basin upstream of the Longfellow Bridge as far as the Harvard Bridge at depths greater than 4 m, the elevation necessary to overtop the berm under the Harvard Bridge. Pockets of saline water were measured in deep holes as far upstream as the Boston University Bridge. From June 23 to June 29, the salt mass in the basin increased by more than 7.1 x 10^6 kg (about 1.2 x 10^6 kg/day), the largest net increase of salt per day observed during the study period. Probably the mass of salt increased because the average daily mean discharge from the Basin between June 23 to June 29 was the minimum for the study period (1.7 m^3/s) and nearly set a historical low based on a 67-year record at a streamgaging station upstream of the Basin in Waltham, Mass.

Between June 29 and July 6, there were 425 lock cycles (an average of 61 lock cycles per day at 10 minutes for each lock cycle) at the new dam. In other words, the locks were open 72 hours during the 7 days between the June 29 and July 6 water-quality surveys. The results from July 6 indicated that the salt wedge had increased in size and salinity since June 29. Although the daily mean discharge increased by about 50 percent—from 1.7 m^3/s on

June 29 to 2.6 m^3/s on July 6—the salt wedge advanced upstream to the John Weeks Bridge at Harvard University. Additionally, most of the Basin at depths greater than 5 m from the Boston University Bridge to the Museum of Science was anoxic.

During the next week, more than 500 lock cycles occurred and the daily mean discharge decreased by more than half from 2.6 m^3/s on July 6, 1999, to 1.2 m^3/s on July 19, 1999, the lowest daily mean discharge estimated during the study period. These low flows and the high number of lock cycles resulted in the salt wedge moving further upstream to a point near Harvard Stadium, affecting about 10 x 10^6 m^3 of the Basin (about 92 percent of the total volume of the Basin). This intrusion represents the maximum extent of the salt wedge and the largest mass of salt observed (over 22 x 10^6 kg) in the Basin during the study period. Most of the Basin at depths greater than 5 m remained anoxic downstream of the Boston University Bridge, from July 6–19, 1999.

A CONCEPTUAL MODEL OF SALT MASS IN THE BASIN

The salt wedge in the lower Charles River is not a stagnant mass of saltwater residing only in the deepest parts of the channel. Rather, it varies in area and salinity throughout the year. Temporal changes in the area and salinity of the salt wedge depend upon the natural forces driving the flow of water through the Basin and anthropogenic influences on that flow. Natural factors include river discharge, precipitation, and stormwater discharges to the Basin. Anthropogenic influences include the operation of the dam at the mouth of the Basin (including lock cycles, pumping, and opening and closing of the lock gates, culverts, sluice gates, and the fish ladder).

A simple conceptual model that explains the importance of these factors on saltwater intrusion into the Basin was developed and tested by using multiple regression analysis. The dependent variable in this model was the change in salt mass in the Basin between water-quality surveys at time 1 (t_1) and time 2 (t_2). The independent variables were the number of lock cycles, the volume of water pumped from the Basin (in cubic meters), a variable (in square meters per hour) related to the area and the time that the fish ladder, lock gates, lock culverts, and sluice gates were open; and the average daily mean discharge (in cubic meters per second) between t_1 and t_2, which was a surrogate for the force of the freshwater discharge (table 2). The force of upstream freshwater is represented by the velocity head (*E*) component of the specific energy equation for a channel with a small slope and is directly related to the upstream discharge (*Q*) by (Chow, 1958);

$$E = Q^2 / 2gA^2 \,, \qquad (1)$$

where

- *Q* is discharge, in cubic meters per second,
- *g* is acceleration due to gravity, in meters per second per second, and
- *A* is cross-sectional area of the lock at the old dam, in square meters.

Two variables, number of lock cycles (*LC*) and average mean daily discharge (*Q*), accounted for 63 percent of the variance of the change in salt mass (ΔSM) in the Basin and were significant at the 90th percentile ($p = 0.1$). The other independent variables accounted for only a small amount of the variance and were not significant ($p > 0.1$). The number of lock cycles was directly related to the change in salt mass in the Basin; as the number of lock cycles increases, salt mass in the Basin increases. In contrast, the average daily mean discharge was inversely related to change in salt mass in the Basin; as the average daily mean discharge or the force due to the upstream freshwater increases, the mass of salt in the Basin decreases.

The empirical model obtained by use of multiple linear regression is as follows:

$$\Delta SM = [(4.2 \times 10^6) \times \log LC] - [(2.5 \times 10^6) \times \log Q] - 6.4 \times 10^6 \,, \qquad (2)$$

where

ΔSM is the change in salt mass between t_1 and t_2, in kilograms,

LC is the number of lock cycles between t_1 and t_2, and

Q is the average mean daily discharge between t_1 and t_2, in m^3/s.

Agreement between the conceptual model and the calculated salt mass in the Basin (r^2=0.92), using the salt mass calculated from measurements taken on June 19, 1998, as the initial mass of salt in the Basin and the change in salt mass calculated using equation 2, indicates that lock operations are the major pathway of saltwater intrusion into the Basin, compared to other possible pathways, such as fish ladders, culverts, and leaking sluice gates (fig 3; table 3). Additionally, this analysis indicates that current dam operations (opening of culvert, lock gates, and sluice gates at low tide, and pumping from the Basin) are not effective in preventing the formation of the salt wedge within the Basin.

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