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Weir River Estuary Flow Study: Hull, Hingham, and Cohasset Massachusetts

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grasses. The upper border is inundated only by occasional spring high tides and lies along the upland edge, at the highest elevations. A few characteristic grasses and shrubs dominate this border between wetland and upland. Between these two extremes of very wet to very dry habitat lies the high marsh, which is flooded by most spring high tides, but may also be continuously free of tidal water for a week or more at a time. Relatively short, fine-stemmed grasses naturally dominate high marsh vegetation. Transitions between low marsh, high marsh and upper border may be gradual or quite abrupt and, although linked by tidal flooding, these three regions are characterized by distinctive assemblages of plants and animals and they are, in many ways, very different environments. Like many natural tidal marshes in Massachusetts, the marsh now occupied by Straits Pond was probably adequately flushed by the exchange of ocean water that would likely not occur through a restrictive tide gate, like the one currently located on Route 228.

In the early twentieth century, the Massachusetts State Board of Health was directed to recommend ways of eradicating nuisance weed growth and foul odors emanating from the pond. One of the recommendations was to enhance flushing of the pond by connecting the eastern end of the pond to the Atlantic Ocean using a network of pipes. This was predicated on the elimination of sewage and waste discharge into the pond. Apparently, no action was taken until the 1940's when interest in the pond was again raised. At this time the Hull Highway Department contracted a consulting engineer to design a tide gate at the outlet of the pond to raise and stabilize the water level. The gate was built and since then has been operated with the goal of improving flushing in the pond. While the gate has been continually operated to control the growth of nuisance weeds in the pond, the problem continues to persist.

Straits Pond is an impoundment that would not occur naturally and is only there because of the presence of the tide gate on Route 228. If not for the restriction offered by the tide gate, Straits Pond would likely be a smaller pond surrounded by a salt marsh. Without ample exchange of Straits Pond water with ocean water the residence time in the pond is longer than it would be naturally. Furthermore, nutrients that build up in the pond due to stormwater runoff are not quickly purged from the system because of the restriction at the gate structure. As such, the pond supports an abundant growth of aquatic vegetation and insects during the summer months. The reduced tidal exchange and increased residence time resulting from the presence of the tide gate has led to significant eutrophication, or hyper-eutrophication, of the pond. Jaworski (1981) describes hyper-eutrophication as indicative of very excessive nuisance conditions, anoxic conditions, and "undesirable" biological communities.

The gates at the Route 228 bridge are manually operated to control the flow rate into and out of Straits Pond by adjusting the gate opening at any period during the tide cycle. The tide gates are on the upstream side of a culvert on Route 228. The culvert is approximately 12 feet wide and has two double gates, which can be adjusted from zero to a 5-foot opening and to a height of approximately 11 feet when completely closed. One set of gates is motorized while the other must be opened and closed manually with a hand crank. The gates are raised and lowered by a center pull setup whereby a vertical rod attached to the center of each of the gates is raised and lowered. One of the problems

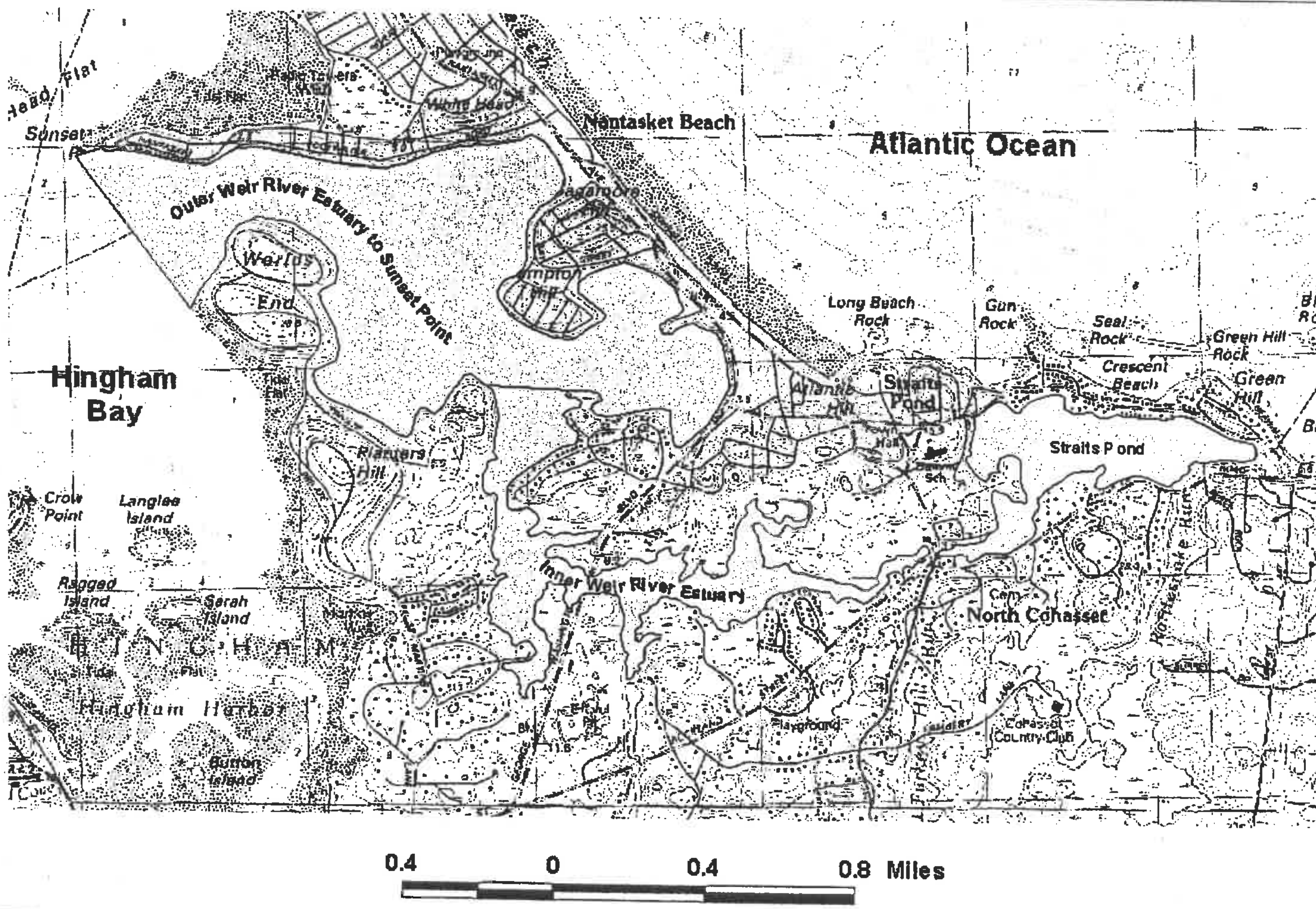

Figure 1-1:
Site Map of Straits Pond and the Weir River Estuary

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2.0 HYDROLOGIC OVERVIEW

2.1 General Hydrology

The watershed of Straits Pond (including the pond) is relatively small at approximately 740 acres and is mostly confined by Route 228, Cedar Street, and Forest Avenue in Cohasset, Massachusetts. Rattlesnake Run is the only significant tributary that drains directly into Straits Pond. This small creek enters on the south side of the pond just east of Windy Hill Road (Figure 2-1). Many storm drains from the peripheral residential areas of Cohasset are also tributary to the pond (IEP, 1980).

The surface area of Straits Pond is 91.4 acres with a mean depth of 3.3 feet; the total volume of Straits Pond is 302 acre-feet. The water depth throughout the pond was relatively uniform as observed during the field surveys conducted during this investigation. The pond area is large relative to the watershed area and the relatively long 71 day (IEP, 1980) average flushing time of freshwater through Straits Pond, or residence time in Straits Pond, necessitates the additional exchange of water through the tide gate at Route 228.

Surface water evaporation from Straits Pond is considered to be a small part of the hydrologic budget. Evaporation in the vicinity of Straits Pond is approximately 26 inches per year (Geraghty et. al., 1973). Assuming that two-thirds of the annual evaporation takes place during summer, 17 inches will have been evaporated during the 90-day summer period (0.016 feet per day). For a 91.4-acre pond this amounts to only 0.74 acre-ft per tide cycle or 0.24% of the pond volume.

The Straits Pond watershed is characterized by numerous bedrock outcroppings, generally shallow soils (<6 feet) with occasional deeper unconsolidated deposits occurring in the large wooded swamps of Cohasset, under the golf course, and at places along the Straits Pond shoreline (IEP, 1980). The Straits Pond shoreline is composed of areas made up of unconsolidated beach and tidal marsh sediments. Areas along the west and south shoreline of Straits Pond appear to be shallow silt and muck deposits which were originally laid down in a tidal marsh environment prior to damming of the pond (IEP, 1980).

Surface water in the watershed generally percolates through the very thin soils and surficial deposits until bedrock is reached. Then water moves along the bedrock/surface deposit interface until emerging as springs or finding an opening in the bedrock. In the area of Rattlesnake Run, the surficial deposits are deep enough to bisect the water table. Therefore, recharge of Rattlesnake Run by groundwater is expected. Finally, groundwater can penetrate bedrock through fractures and faults. This process could possibly be the source of groundwater recharge to Straits Pond. However, while not insignificant, this source of recharge is inadequate for flushing or dilution (IEP, 1980).

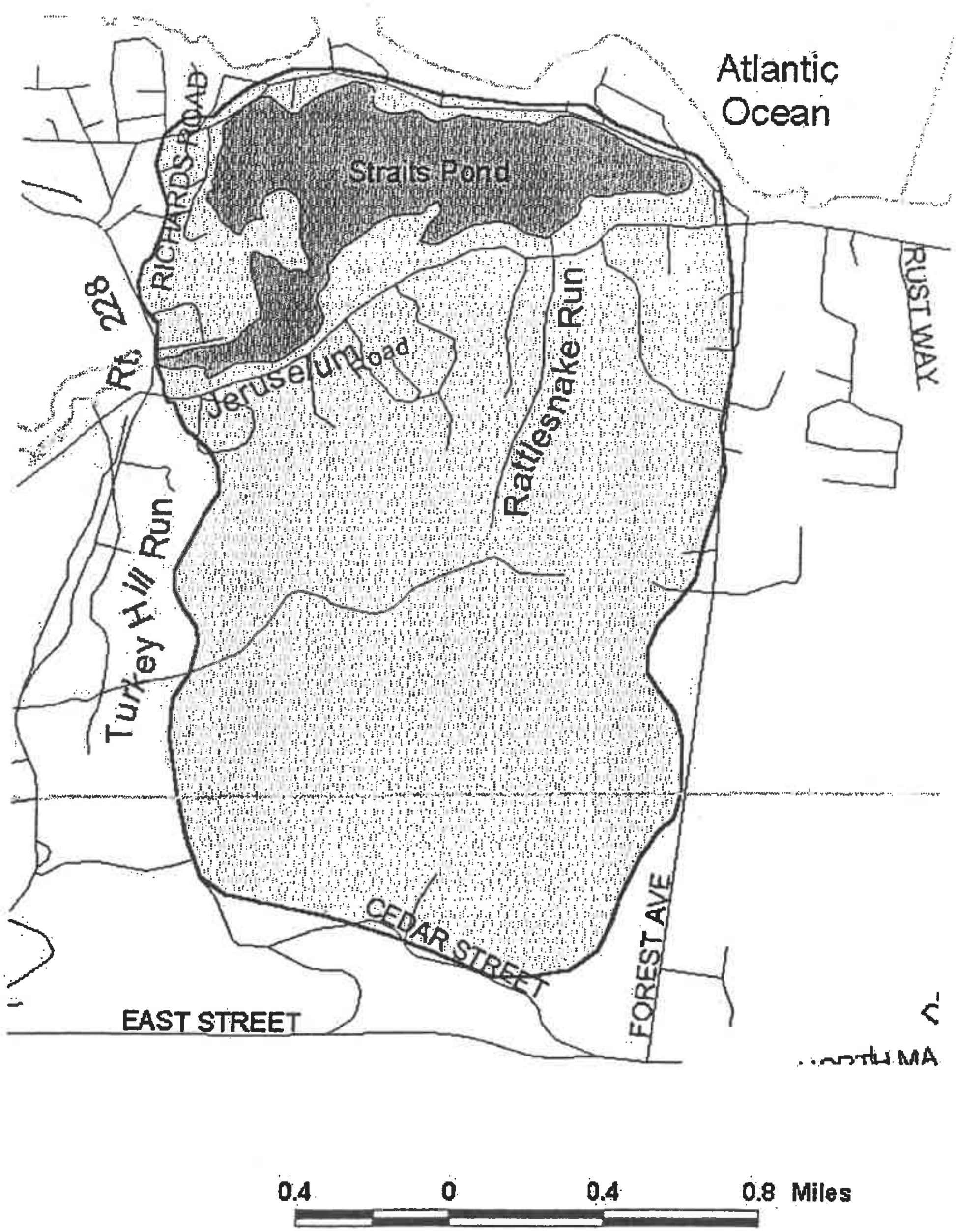


Figure 2-1:
Site Map of Straits Pond
and Straits Pond Watershed Boundary

3.0 METHODOLOGY

3.1 Field Methods

Both hydrological and water quality information was collected during this investigation to aid in the development of a water budget of the Straits Pond/Weir River Estuary system. The physical measurements were primarily collected to facilitate the development of water budget and dilution calculations while the water quality data were collected so that hypotheses about mixing could be proposed and tested. The field-sampling portions of the investigation included the collection of basic hydrological and water quality information during each of two surveys. The first field survey was conducted on May 15, 2001 to represent average runoff rates during the spring season (Figure 2-2). The second field survey was conducted on August 29, 2001 to represent low flow rates during the summer season. Similar measurements were made during each of these two surveys for comparative purposes. The following list of hydrologic and water quality information was collected in Straits Pond and the Weir River Estuary during each of the two surveys.

1. Streamflow measurements were made in Rattlesnake Run (at Jerusalem Road) at Station G1 (Figure 3-1) and in the Weir River (at Route 228) at Station G2 (Figure 3-2) to determine the contribution of surface water to Straits Pond and the Weir River Estuary, respectively.

2. Water quality data was collected including salinity, dissolved oxygen (D.O.), pH, and temperature in both Straits Pond and the Weir River Estuary. In the estuary, measurements were collected at both high and low tides to illustrate the difference between the two drastically different water levels. Oxygen and pH measurements were made to provide a cursory view of the water quality in the system; however, these measurements were not an integral part of this hydrologic interpretation. The temperature and especially the salinity measurements were used to characterize the mixing of pond water with estuary water during successive tide cycles. The six water quality sample stations in Straits Pond (S1 through S6) were distributed along the long axis of the pond (Figure 3-1) to reflect changes in water quality from the tide gate to the furthest distance from the gate. The seven water quality sample stations in the Weir River Estuary (W1 through W7) were located from the tide gate downstream to George Washington Boulevard (Figure 3-2). Since gradient in salinity was not expected downstream of George Washington Boulevard, measurements were not made beyond this point.

3. Volunteers from the Straits Pond Watershed Association (SPWA) measured water stage at the Route 228 tide gate. On May 10, 2001, ENSR installed two staff gages measurable to $1/100^{th}$ of a foot on the upstream and downstream side of the Route 228 bridge structure to facilitate these measurements. Measurements were made upstream of the tide gate in Straits Pond and downstream of the tide gate in the Weir River Estuary. These measurements were made during each of the two surveys and were collected throughout most of an entire tide cycle in conjunction with the other water measurements.

assuming that the volume of original water left in Straits Pond, after η exchanges, is equal to the initial volume multiplied by the percent of water remaining between exchanges (dilution), raised to the η power (Equation 1). The turnover rate was calculated based on the stage changes measured during each successive tidal flushing giving an indication of the effectiveness of a particular gate operation scheme.

Equation 1: $$V_f = V_i \cdot D^\eta$$

Where: V_f = final volume of original pond water (ft^3); V_i = initial volume of pond water (ft^3); D = dilution during each exchange; η = number of exchanges.

5. With the dilution calculations complete, the amount of volumetric exchange required for a calculated turnover rate was compared with the tide gate rating curves. This comparison was made to determine the turnover and dilution currently taking place in the pond and to determine the maximum dilution that could be developed using the currently configured gate system.

6. Finally, a dynamic flow and transport model was developed for the Inner Weir River Estuary to illustrate the transport of water from Straits Pond through the Inner Weir River Estuary and out to Worlds End. The Outer Weir River Estuary was excluded from this analysis after a simple box model indicated that the Inner Estuary alone provides significant dilution of water released from Straits Pond (See Section 5.5.5). The development of this dynamic model was not part of the original scope of this investigation. However, the model is useful as a potential tool for examining the effects of different release schemes on the flushing of pond water from the system.

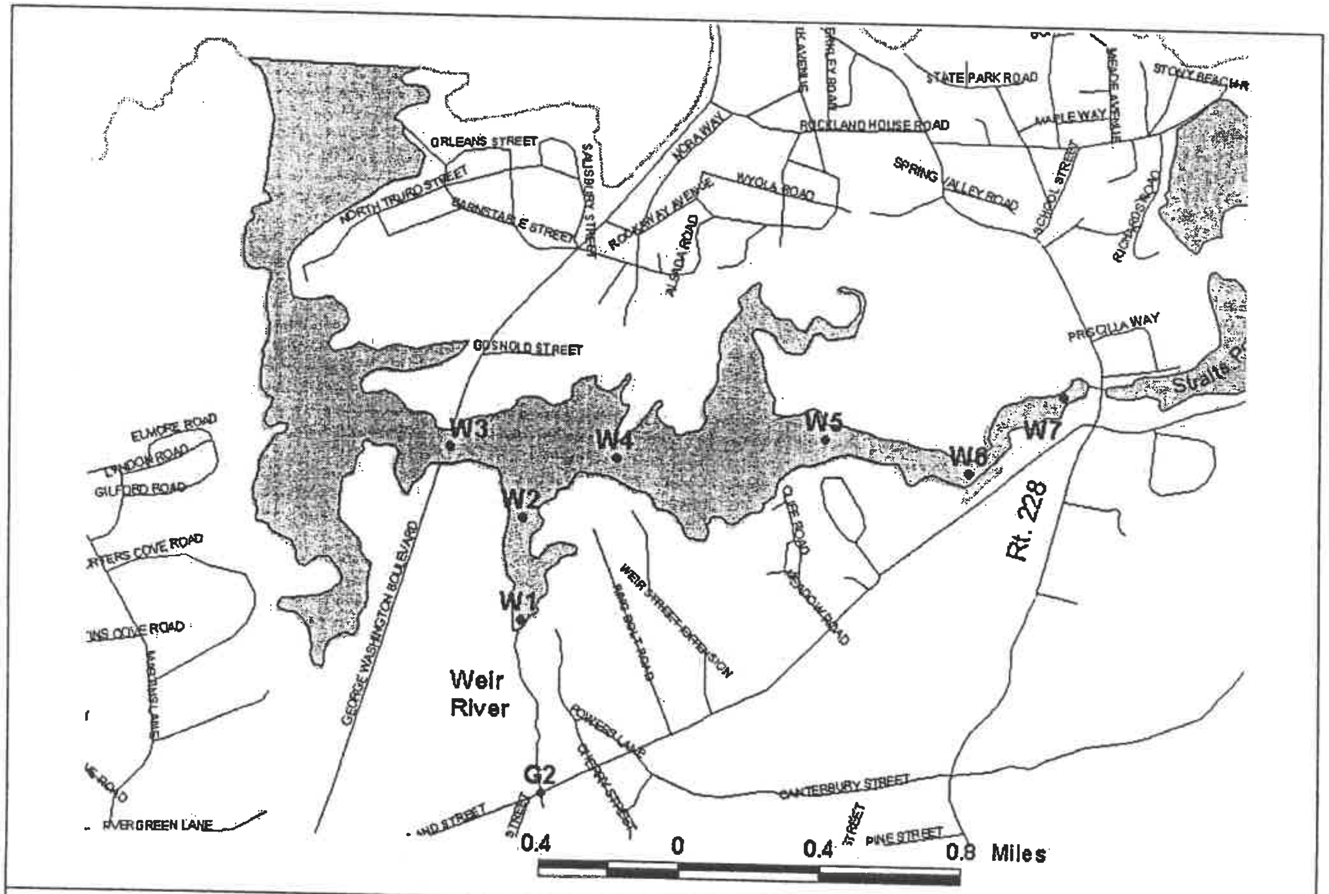


Figure 3-2:
Map of Inner Weir River Estuary Showing Sample Locations

providing a generalized snapshot of the Weir River Estuary at both ends of the tide cycle. Not capturing the exact high and low tides is not expected to change the results of the investigation. During the early morning, flow rates through the tide gates were measured at various gate configurations. Gate opening and duration was not recorded during the day, however, the gate was only operated to facilitate the flow measurements and not specifically to flush water from Straits Pond. While some water left the pond during the release, to accommodate the flow measurements, the release was 1) only from one gate at a time, 2) at relatively minimal gate openings (closed, quarter open, and half open), and 3) of a relatively short duration (less than one-half hour total). Therefore, the water level in the pond was not expected to change noticeably during the survey. During late morning and early evening, at low and high tide respectively, hydrologic and water quality information was collected in the Weir River Estuary and during the afternoon similar information was collected in Straits Pond. Every 30 minutes throughout the day, volunteers from the SPWA measured the water stage upstream and downstream of the tide gate on Route 228. These water levels are illustrated in Figure 4-2.

The tide data reported by NOAA (Figure 4-1) and measured at the Route 228 bridge (Figure 4-2) illustrates an important feature of the Straits Pond and Weir River Estuary system, in that the tidal variation between successive high and low tides is significant. Figure 4-1 indicates that the difference in Boston Harbor can be as much as 11 feet during a spring tide, without the compounding effects caused by storms, but was only 7 feet during the May 15th survey. Furthermore, while there was a 7 feet tide difference predicted for Boston Harbor the tide difference measured at Route 228 was only 5 feet indicating that at the Route 228 bridge the tide range is somewhat diminished. This significant difference between high and low tide can result in a relatively large tidal prism, and correspondingly high dilution flushing rate as large volumes of water from outside the estuary are continually exchanged during each successive tide cycle. Compared with an estuary having a relatively small tidal prism, and similarly minimal freshwater inflow, the Weir River Estuary flushes at a much faster rate. This high flushing rate is particularly true in shallow estuary systems like the Weir River Estuary. Furthermore, while the rate of water level change is similar in Boston Harbor and in the Weir River Estuary throughout most of the tide cycle, the stage in the estuary at Route 228 is relatively constant throughout the period of low water.

In addition to providing information related to water levels in the Weir River Estuary, the stage data collected by SPWA volunteers illustrates the effect of a release of water from Straits Pond on the stage in the pond. The stage data collected in Straits Pond on May 15th (Figure 4-2) indicates that the stage change in Straits Pond was negligible during the survey, even though water was being let out of the pond for flow measurements. This is because of the relatively large surface area of the pond and the subsequently large water volume associated with even a small change in water level.

The water quality measurements made in the estuary and in Straits Pond included D.O., pH, salinity, and temperature. These measurements were made to assess the dilution of pond water into the estuary during successive high and low tides. Furthermore, the measurements were designed to illustrate both hydrologic and water quality differences between the average and low flow periods. Water quality data from the first survey on May 15th is summarized in Table 4-1. The "NA" in the tide column indicates that because the water level in the pond is independent of the tide in the estuary measurements of tide elevations during the pond survey were not necessary.

Streamflow was measured in both Rattlesnake Run (Figure 3-1: Station G1) that flows into Straits Pond and in the Weir River (Figure 3-2: Station G2) that flows into the Weir River Estuary upstream of George Washington Boulevard. The flow rate measured at Rattlesnake run was 0.04 cfs and the flow rate in the Weir River was 7.24 cfs.

Finally, several attempts were made to install mini-piezometers in locations (P1 through P4) at the perimeter of Straits Pond during the May 15th survey (Figure 3-1). This was done to determine the hydraulic gradient between the pond and the underlying groundwater. It was not possible to penetrate the thick layer of dense silt lining the bottom of Straits Pond to obtain a representative sample of groundwater. In most cases, the mini-piezometers were installed to depths of approximately 18 inches; however, water withdrawn from the mini-piezometer had similar water quality as the overlying pond water. The measurements collected during the survey suggest that dilution by groundwater is probably minimal which is what was concluded in the IEP (1980) report.

4.2.2 August 29, 2001 Survey

The second field survey was conducted on August 29th to capture low flow conditions during the summertime. High Boston Harbor tide levels on August 29th occurred at 9:00 a.m. and 9:11 p.m. and low tide occurred at 2:43 a.m. and again at 2:50 p.m. The tide reported by NOAA (http://co-ops.nos.noaa.gov/data_retrieve.shtml) for Boston Harbor at Boston Light for the 5 days prior to and 2 days after August 29th is illustrated in Figure 4-3. The study coincided with the period from the morning high tide through the afternoon low tide. ENSR collected water quality measurements in the estuary during the morning high tide and again during the afternoon low tide. Records indicate that the gate was not operated during the survey. Water quality measurements were made in Straits Pond during the early afternoon. Similar to the May survey, flow rates were measured in both Rattlesnake Run and in the Weir River. Volunteers from the SPWA measured water stage upstream and downstream of the tide gate on Route 228 from the morning high tide through the evening high tide (Figure 4-4). The stage of the pond was difficult to read early in the survey because of the presence of muck on the staff gage. This problem was solved in late morning when ENSR field staff cleaned the gage from a boat.

The results of the tide measurements in Boston Harbor as reported by NOAA and at the Route 228 bridge, as measured during the survey illustrate similar results as those from the first survey. The difference between the high and low tide in Boston Harbor was similarly large, extending to 7 feet during the survey but was up to 10 feet less than a week earlier. Furthermore, while there was a 7 feet tide difference predicted for Boston Harbor the tide difference measured at Route 228 was only 6 feet indicating again that at the Route 228 bridge the tide range is somewhat diminished. The water level measurements in the estuary show a similar trend at the low water period of the tide cycle where water levels tend to remain constant for an extended period. Results of the stage measurements in the pond are similarly to measurements made during May in that they were constant; however, the measured stage during August was about 1 foot lower.

The water quality measurements made in Straits Pond and the Weir River Estuary included D.O., pH, salinity, and temperature. These measurements were made to illustrate the dilution of pond water into the estuary during successive high and low tides. Furthermore, the measurements were designed to illustrate both hydrologic and water differences between the average and low flow periods. Water quality data from the second survey on August 29th is summarized in Table 4-2. The "NA" in the tide column indicates that because the water level in the pond is independent of the tide in the estuary measurements of tide elevations during the pond survey were not necessary. The "NA" in the D.O. and D.O. Sat. columns indicates that there was a problem with the oxygen sensor and the data was not valid.

measured during May are indicative of the lack of flushing through the tide gate during the winter months. In contrast, the higher salinity in Straits Pond measured in August indicates the effects of controlled flushing during the summer months. This is compounded by the fact that apparently very little groundwater enters Straits Pond to dilute the more saline water entering the through the tide gate. Since the salinity of the water in the estuary and the pond were determined to be similar, it is not surprising that there is no salinity gradient in the upstream reaches of the estuary at low tide like there was during the first survey. Water temperatures measured in both the estuary and the pond were higher during the second survey because of the warmer ocean water and air temperatures. The D.O. measured during the August 29, 2001 survey were invalid because of a faulty D.O. sensor on the water quality meter used during the survey. While the lack of D.O. data is unfortunate, it does not invalidate any of the assumptions made as a result of the survey since the oxygen concentrations were not used to determine dilution.

4.3 Tide Gate Flow Measurements

The tide gate structure at Route 228 consists of two mechanical gates. Each is similar in design but one is operated electrically and the other is operated manually. As part of the field investigation a series of flow measurements were made at the outlet of the tide gate structure to determine the flow rates that would result from different gate openings under different upstream/downstream stage differences. One set of measurements was made on May 10th during an initial site visit and another was made on May 15th during the first intensive survey. To capture the variability in flow rate from each of the gates under different hydrologic conditions, flow measurements were made while operating each gate individually. Flow through the gates was measured with the gates closed, and then opened both one-quarter and one-half way at a representative stage difference. Flow rates through the gates could not be measured at gate openings greater than halfway because of the extremely high velocities induced in the channel underneath the Route 228 bridge. The head difference decreased at increased gate openings during the May 10th survey because the tide was going out during the measurement period. During the May 15th survey, the tide was coming in and the head difference decreased during the measurement period. The flow rates and coincident stage differences and gate openings are illustrated in the following Table 4-3. As indicated in the table the change in gate opening has a greater effect on the flow rate through the gate than the slight (less than 1 foot) change in head difference, which occurred during the measurement period.

5.0 DATA ANALYSIS AND INTERPRETATION

5.1 Physical Dimensions

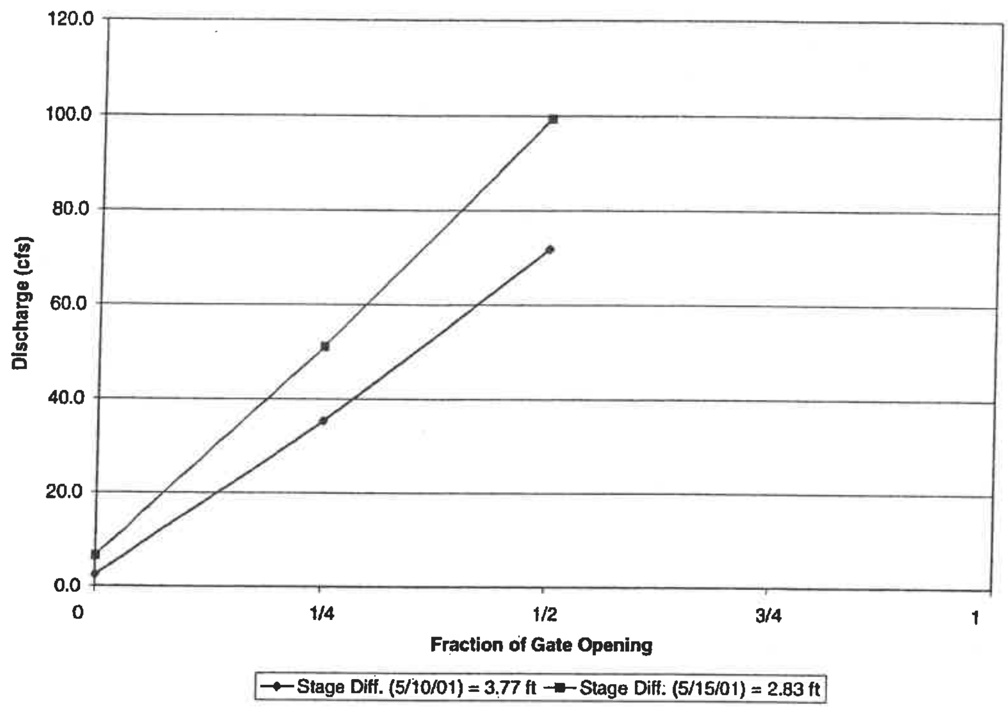
In order to develop quantitative estimates of flushing and dilution in the Straits Pond and Weir River Estuary a fairly accurate representation of the bathymetry and subsequently the volume and surface area of each must be developed. The surface area, depth, and volume of Straits Pond were determined from a previous investigation by IEP (1980). The bathymetry and surface area of the Weir River Estuary was determined from a NOAA navigational chart of Boston Harbor. Because much of the areal extent of the Inner and Outer Weir River Estuary is occupied by tidal flats that are exposed near mid tide and completely covered only near high tide, a conservatively small surface area representing about 50% of the measurable surface area was used during the volumetric calculations. By reducing the surface area in this way the volume calculations are not artificially biased high and the residence time is not calculated to be unrealistically long. A summary of the geometric information relevant to Straits Pond and the Weir River Estuary is illustrated in the following Table 5-1.

Table 5-1: Physical dimensions of the Weir River Estuary and Straits Pond (Figure 1-1).

Weir River Inner Estuary (Route 228 to Worlds End)		Weir River Outer Estuary (Worlds End to Sunset Point)		Straits Pond	
Parameter	Value	Parameter	Value	Parameter	Value
Surface Area (acres) at 50%	69	Surface Area (acres) at 50%	243	Surface Area (acres) at 100%	91.4
Low Water Stage (ft)	1.0	Low Water Stage (ft)	1.0	Depth (ft)	3.3
High Water Stage (ft)	9.0	High Water Stage (ft)	9.0	Volume (acre-ft)	302
Low Water Avg. Depth (ft)	6.4	Low Water Avg. Depth (ft)	10.0		
Low Water Volume (acre-ft)	442	Low Water Volume (acre-ft)	2,427		
Tidal Prism (acre-ft)	555	Tidal Prism (acre-ft)	1,941		

The average depth in the Inner Estuary at low water is 6.37 feet and the average depth in Outer Estuary at low tide is 10 feet. The average depth in the pond is 3.3 feet. The average low water and high water stage in the estuary was estimated to be from 1.0 to 9.0 feet to generally correspond to the stage difference measured in Boston Harbor. Using these two high and low water stages and assuming that the surface area in the main channel through the long axis of the estuary does not change between high and low tide, the tidal prism was calculated. The tidal prism, defined as the

Figure 5-2: Electrically Operated Gate Stage-Discharge Relationship.



Rating curves were developed by plotting the streamflow data collected during a reconnaissance survey and during the first field survey. The head difference indicated in Figures 5-1 and 5-2 was measured as the difference between Straits Pond and the Weir River Estuary at the time of the flow measurement. Greater differences in water stage would result in a steeper rating curve slope while smaller differences in stage would result in a shallower rating curve slope. For the analyses presented in the analytical portion of this investigation, the results presented in the aforementioned rating curves at a stage difference of roughly 3.5 feet is used to approximate the average head difference during any potential release period whereby the head difference changes significantly during the release. A more detailed rating curve analysis of the gates at different head differences would yield more information that could be applied under a variety of conditions. However, it will be shown that at gate openings of only half, more than 10% of the water in the pond can be released in only 3 hours. Therefore, a 2-hour window of 3.5 feet head difference could easily be met to let water out of the pond and a head difference of at least 2-feet could be met over a 2-hour window to let water back into the pond (Figures

5.4 Release/Refill Potential Based on Measured Data

The tide gate at Route 228 is currently operated to release water when the stage in the pond is greater than the stage in the estuary and refill the pond when the opposite is true. Figures 4-2 and 4-4 demonstrate that the stage in the pond was greater than the stage in the estuary by 4 feet for several hours during the May survey and 3.5 feet for several hours during the August survey. While the flow rating curves suggest that this difference is enough to release 0.4 feet of water during a single tide cycle the potential to refill the pond during a single tide cycle can be diminished by the reduced head difference between the estuary and the pond at high tide. During the August survey the stage in the estuary was 2 feet greater than that in the pond for approximately 2 hours; however, during the May survey the stage in the estuary was only about 1 foot greater than that in the pond, possibly for as long as 2 hours. Therefore, based on the potential stage difference between the estuary and the pond as measured during each of the two surveys the factor limiting the exchange of water between the estuary and the pond is the ability to refill the pond during high tide. While it is recognized that during the survey of May 15, 2001 the ability to refill the pond at high tide was limited there are several other factors to consider before assuming that the system is always limited in this fashion.

1. If 0.4 feet of water were released from the pond on an outgoing tide then by definition there would be an additional 0.4 feet of head difference available on the incoming tide to let water back into the pond. The additional head difference would act to allow more water to enter the pond through the tide gates to replace the water that was released. During the May and August surveys no such release had occurred in the recent past indicating that the stage difference could have been greater by the amount released from the pond.

2. Throughout this report the evaluation regarding letting water into and out of Straits Pond was always completed with a maximum gate opening of halfway. While rating curves were not developed for larger gate openings it is assumed that opening the gates all the way would allow more water to pass both into and out of the pond.

3. During the May 15, 2001 sample survey the maximum tide predicted for Boston Harbor was relatively low compared with tides both earlier and later in the month (Figure 5-3) indicating that the maximum tide stage in the estuary would be higher at most other times of the month. The same scenario occurred during the August 29, 2001 sample survey. In fact, an examination of the entire 2001 tide record indicated that the daily maximum high tide in Boston Harbor was higher than the May 15, 2001 maximum (Figure 4-2) 95% of the time and was higher than the August 29, 2001 maximum (Figure 4-4) 76% of the time. This analysis indicates that the possible tidal inflow limitation during the May survey can be considered a worst case scenario.

4. Finally, During the period from May 16 through May 18, 2001, Straits Pond gate records indicate that enough water was released from the pond to lower the water level by 2 feet, at a maximum tide height similar to that measured during the survey of May 15, 2001 (Figure 5-3). The same

summer 2001 period when the growth of aquatic vegetation was excessive. While the above analysis is not conclusive, the data suggests that the current gate configuration can be used to transfer significant volumes of water both into and out of the pond during most tide cycles. A more detailed analysis, beyond the scope of this effort, would be necessary to determine an optimal release schedule.

5.5 Flushing and Dilution Analyses

The hydrologic data collected during each of the two surveys and the area/volume information for the Weir River Estuary and Straits Pond was used to calculate 1) the potential dilution of Weir River water in the Inner Estuary and Rattlesnake Run water in Straits Pond, and 2) the potential turnover rate in the pond. Dilution of Straits Pond water into the Outer Estuary was also considered. Additionally, the volumes of water from Straits Pond were translated into relatively short duration flow rates and then to gate openings. This was done so that the information developed from this analysis could be used to assess improvement of the flushing in the pond by optimizing the control of the gates currently in use at the Route 228 bridge.

5.5.1 Inner Estuary Dilution of the Weir River Inflow

Fresh water from the Weir River enters the estuary immediately upstream of George Washington Boulevard (Figure 1-1). Since the water from the estuary is currently flushed into Straits Pond through the Route 228 gate structure there is some potential for freshwater from the Weir River to have an impact on Straits Pond. While nutrient concentration data was not collected for the Weir River during either of the two surveys, the flow rate was measured. As already mentioned, the Weir River flow measured on May 15th was 7.24 cfs and the flow measured on August 29th was 1.19 cfs. Since the volume in the Inner Estuary at high tide has already been determined (Table 5-1) to be 997 acre-feet (low water volume plus tidal prism) the dilution of the Weir River inflow can be determined by dividing the total estuary volume by the total inflow volume over a single 12.5 hour tide cycle.

The dilution ratio of river water to water in the Inner Estuary water (Figure 1-1) was determined to be 1:133 using the Weir River inflow rate measured in May and a dilution ratio of 1:811 was determined using the Weir River inflow rate measured in August. The very high dilution ratios calculated for both surveys suggests that inflow from the Weir River likely has no effect on the water quality of the Inner Estuary and subsequently Straits Pond, regardless of the Weir River inflow concentrations. This is particularly true during the low flow August survey when nutrient concentrations in the Weir River would likely be greatest.

Since the precipitation during an average May is roughly only 3 times that measured during May 2001 (Figure 2-2), the flow of the Weir River and Rattlesnake Run may have been greater if conditions were closer to the normal long term average. Higher measured flows would have increased the likelihood that water from the Weir River would enter Straits Pond during inflow through the tide gates. However,

5.5.4 Straits Pond Flushing Rate

Dilution of Straits Pond water by water from the Weir River Estuary is the primary goal of operations at the tide gate on Route 228. Therefore, comparing the actual volume of water released from the pond during ebb tide and then reintroduced to the pond during flood tide is necessary to determine the net flushing rate. As indicated in Table 5-1, the average depth in the pond is 3.3 feet and the volume of water in Straits Pond is 302 acre-feet feet. Because the depth throughout the pond is mostly uniform, as indicated during the field investigation of May 15th, a complex relationship between volume and stage is not necessary to calculate the volume of water released for a given drawdown in stage. Therefore, to determine the volumetric withdrawal from the pond resulting from a given drawdown, the pond surface area (Table 5-1) is multiplied by the drawdown. By further dividing the water volume released and reintroduced to the pond, by the net water volume in the pond, the single tide cycle dilution can be calculated. Furthermore, the number of consecutive exchanges that would result in a 95% exchange can also be calculated (Equation 1). Both the single release dilution and the number of exchanges necessary to achieve an arbitrary 95% turnover are illustrated in the following Table 5-3.

Table 5-3: Dilutions and number of exchanges to reach 95% for Straits Pond.

Drawdown/ Refill (ft)	Resulting Pond Dilution	Tide Cycles to 95% Exchange
0.1	3%	97
0.2	6%	48
0.3	9%	31
0.4	12%	23
0.5	15%	18
0.6	18%	15
0.7	21%	13
0.8	24%	11
0.9	27%	9
1.0	30%	8

The Straits Pond dilution calculations in Table 5-3 indicate that by releasing 0.1 feet of water from Straits Pond, and then reintroducing that same amount from the estuary, dilutes the pond by 3% and would need to be done 97 times to exchange 95% of the water in the pond. Even exchanging 0.4 feet of water in the pond would result in a 12% dilution and would need to be done 23 times to reach a 95% exchange rate. This analysis indicates that a significant volumetric exchange is necessary to effect the short-term water quality of Straits Pond.

5.5.5 Estuary Dilution of Straits Pond Inflow

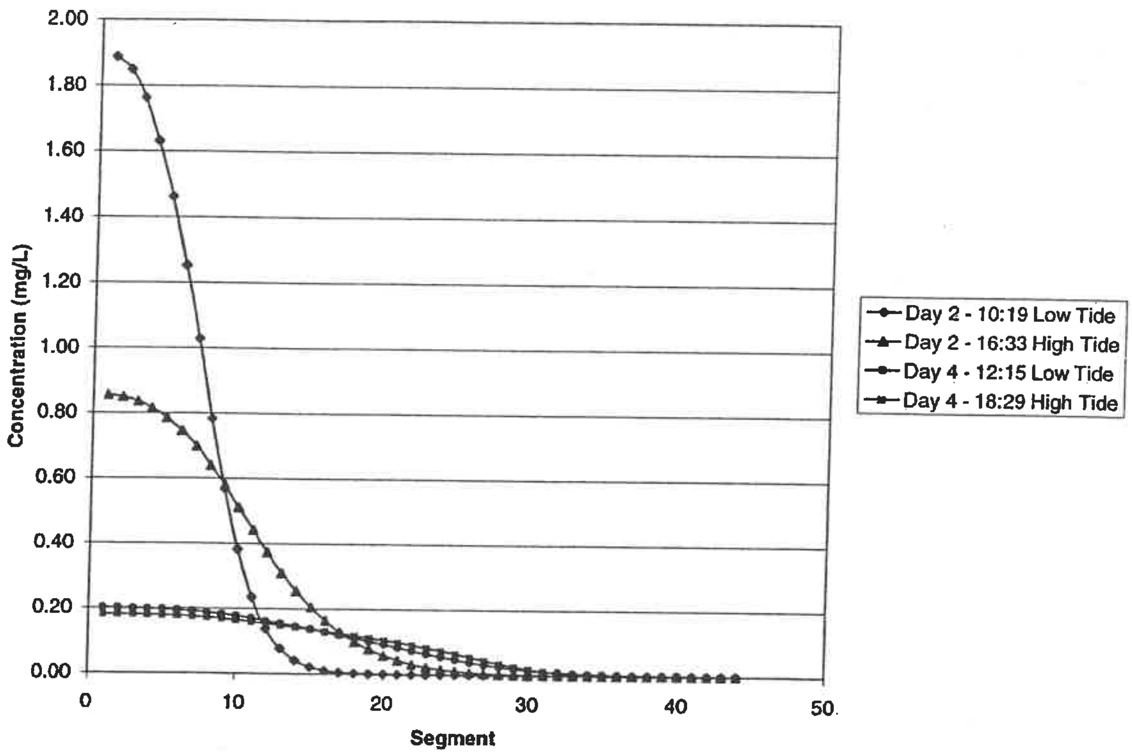
Determining the dilution of Straits Pond water into the Inner Weir River Estuary is a simple calculation if two assumptions are made, 1) the Inner Weir River Estuary is completely mixed, and 2) water can be released from Straits Pond instantaneously. While neither of these assumptions is entirely true the simple "box model" analysis provides a valuable insight into the potential for the Inner Estuary to dilute water discharged from Straits Pond. The dilution of pond water into the Inner Estuary during a single tide cycle is calculated by dividing the volume of the Inner Estuary at high tide by the volume of water released from the pond during a single tide cycle. This procedure can also be used to further dilute the water in the Inner Estuary with water from the Outer Estuary, as water leaving the system is replaced with new water in Hingham Bay. Table 5-4 indicates that if 0.4 feet of the pond water were mixed with a single Inner Estuary volume, the ratio of pond water to Inner Estuary water would be 1:27 and this would be further diluted to 1:119 once in the Outer Estuary. The dilution of pond water into estuary water can be determined through two successive tide cycles. This is done by assuming that the water released from the pond completely mixes with the water volume in the estuary, then a volume equal to the tidal prism is removed and replaced with the same volume of new water. This new water then further dilutes the pond water/estuary water mixture left at low tide. Figure 5-4 indicates that if 0.4 feet of the pond water when diluted twice in this fashion the ratio of pond water to Inner Estuary water would be 1:61 and this again would be further diluted to 1:215 once in the Outer Estuary.

Table 5-4: One and two tide cycle dilutions of Straits Pond water in the Weir River estuary.

Drawdown/ Refill (ft)	1 Tide Cycle Dilution (Route 228 to Worlds End)	2 Tide Cycle Dilution (Route 228 to Worlds End)	1 Tide Cycle Dilution (Worlds End to Sunset Pt.)	2 Tide Cycle Dilution (Worlds End to Sunset Pt.)
0.1	109	246	478	860
0.2	54	123	239	430
0.3	36	82	159	287
0.4	27	61	119	215
0.5	22	49	96	172
0.6	18	41	80	143
0.7	16	35	68	123
0.8	14	31	60	108
0.9	12	27	53	96
1.0	11	25	48	86

The dilution of pond water in the inner and outer Weir River estuary is significantly greater during the second tide cycle than during the first. Therefore, unless only a very small volume of water is released from the pond, reintroducing water to the pond from the estuary during the next incoming tide can be

Figure 5-5: Weir River Estuary Tracer Concentration Showing Low & High Tide (Release at Day 2 - 05:00 to 07:00)



The results of the hydrodynamic and water quality model (Figure 5-5) indicate that water released from Straits Pond is not immediately mixed with the water in the Inner Estuary. At the low tide immediately following the release (Day 2), tracer concentrations are much higher near the tide gate (Segment 1) than out near Worlds End (Segment 44). Even at the next high tide, concentrations are still high near the tide gate and have only been reduced due to mixing and subsequent dilution with the incoming tidal water. However, the tracer is mixed rapidly by successive tidal inflows and by the end of the first four tide cycles (Day 4) following the introduction of the tracer the initial concentration is reduced by approximately a factor of 10 near the tide gate. The dilutions predicted using the model are not as favorable as dilutions calculated with the complete mixing assumption but are more realistic because of the dynamic nature of the model predictions. The model results indicate that the Inner Estuary has the capacity to effectively exchange water from the Outer Estuary with water from Straits Pond if the pond water is allowed purge from the Inner Estuary over as few as 4 successive tide cycles.

7.0 RECOMMENDATIONS

Based on the hydraulic and water quality results of this investigation the following recommendations are being made:

- Simple calculations can be made to gain a better understanding of the flow rate when the gates are fully open. The average volumetric flow rate measurements can be made during gate releases by maintaining a constant gate opening for a specific time period and noting the starting and ending stage in the pond during the release. Dividing the volume released (decline in stage multiplied by the surface area) by the release time results in the average flow rate. This would only be effective during releases large enough to significantly effect the stage in the pond. If this approach does not provide the desired level of detail then a more detailed and focused investigation should be considered to gain a better understanding of the gate operations.

- Based on the results of this investigation a modified release scheme should be implemented to increase flushing from the pond. For example, the study results indicate that it is possible to transfer 0.4 feet of Straits Pond water through the current gate configuration over a period of 3 hours. Furthermore, an exchange of 0.4 feet of Straits Pond water results in an exchange of 12% of the pond water, requiring 23 exchanges to result in a 95% turnover rate. Also, the modeling results indicate that it takes at least 4 tide cycles (approximately every other day) for water to effectively flush from the estuary. Therefore, if 0.4 feet of water is released from the pond on the outgoing tide every eighth tide cycle (~4 days), and 0.4 feet enters the pond on the incoming tide every eighth tide cycle (~4 days), and if the release and inflow are out of phase by four tide cycles (~2 days), then the pond can achieve a 95% exchange in only 46 days. This assumes a relatively short mixing time in the Straits Pond. If complete and rapid (2 days) mixing does not occur in the pond then the time to 95% exchange could be longer. This release and inflow scheme could also be effected by operational modifications necessary to prevent flooding.

- A modified release scheme at the tide gates at Route 228 should be implemented and water quality parameters monitored to determine whether a significant improvement in water quality in Straits Pond results. It has been mentioned that surface algae in Straits Pond can get caught around the vertical posts attached to the tide gates, effectively limiting the amount of water released from the pond. To minimize this problem, a modification to the gate should be considered which would replace the center pull setup with a mechanism to raise and lower the gate at the sides. Currently, only one of the tide gates is operated electronically; the other operates by turning a cumbersome and difficult to operate hand crank. This mechanical setup should be upgraded with an electric motor, similar to that currently being used on the electrically operated gate, to make it more usable. Upgrading the mechanical gate to an electrically operated gate would need to occur regardless of the gate size.

8.0 REFERENCES

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