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Stump Brook / Monponsett Pond

Hydrologic and Water Quality Assessment

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Massachusetts Division of Ecological Restoration
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

At the request of the Massachusetts Division of Ecological Restoration (DER), the Horsley Witten Group, Inc. (HW) is pleased to present this assessment of potential water management scenarios regarding the use of water from Monponsett Pond in Halifax and Hanson, Massachusetts by the City of Brockton, Massachusetts. As detailed most recently in the 2013 Sustainable Water Management Initiative (SWMI) Report prepared by Princeton Hydro, LLC, in response to severe drought in the 1960s the City of Brockton began transferring water from Monponsett Pond and Furnace Pond (Pembroke, MA) to the City's primary water supply source of Silver Lake in Kingston, Plympton, Pembroke, and Halifax (Princeton Hydro, 2013).

Brockton's water supply diversions from surface water resources in Kingston, Pembroke, Halifax, Hanson, and Plympton are complex and controversial. They are frequently referred to as "Tri-basin" water diversions because the diversions transfer water between three separate watersheds (Figure 1):

1) Water is transferred from Furnace Pond in the North River Watershed to Silver Lake in the Jones River Watershed;
2) Water is transferred from Monponsett Pond in the Taunton River Watershed to Silver Lake and;
3) Water is transferred from Silver Lake for final use by Brockton in the Taunton River Watershed.

Monponsett Pond

The subject of this study in the Tri-basin area is Monponsett Pond and its outflow through Stump Brook. Monponsett Pond consists of West Pond and East Pond divided by a narrow causeway of both natural and anthropogenic origins. The only surface water connection is an approximately eight-foot wide by six-foot high box culvert at the southern end of the causeway (Figure 2) (culvert dimensions from DER and the Monponsett Watershed Association (MWA)). Natural surface water flow from Monponsett Pond occurs via Stump Brook which originates at the northwestern end of West Pond (Figure 1). Stump Brook eventually contributes to the Satucket River, which in turn flows to the Taunton River further southwest. The Brockton water diversion inlet is located at the southeastern end of East Pond (Figure 1 and 2). At the time of the construction of the diversion pipe in the 1960's, a dam was rebuilt (at higher elevation) on Stump Brook, approximately a half mile downstream from the West Pond outlet, for the purpose of better retaining water in the Pond to feed the Brockton diversion (Figure 2). The dam increased the available storage in Monponsett Pond to supply Brockton's diversion but also, as a necessary corollary, reduced streamflow out through Stump Brook.

Figure 1. Tri-Basin Watersheds and Primary Water Resources and Diversions (From Princeton Hydro, 2013)

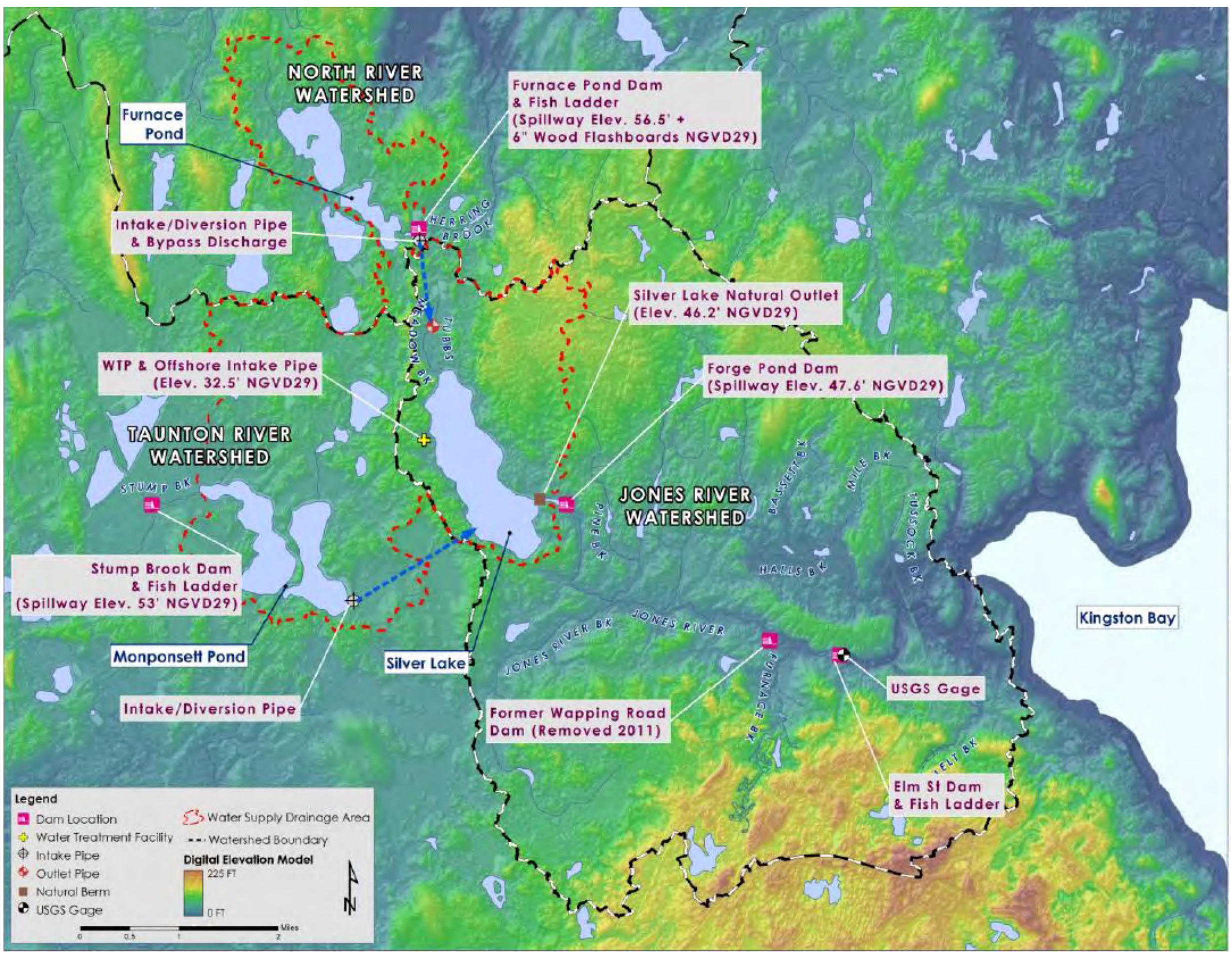


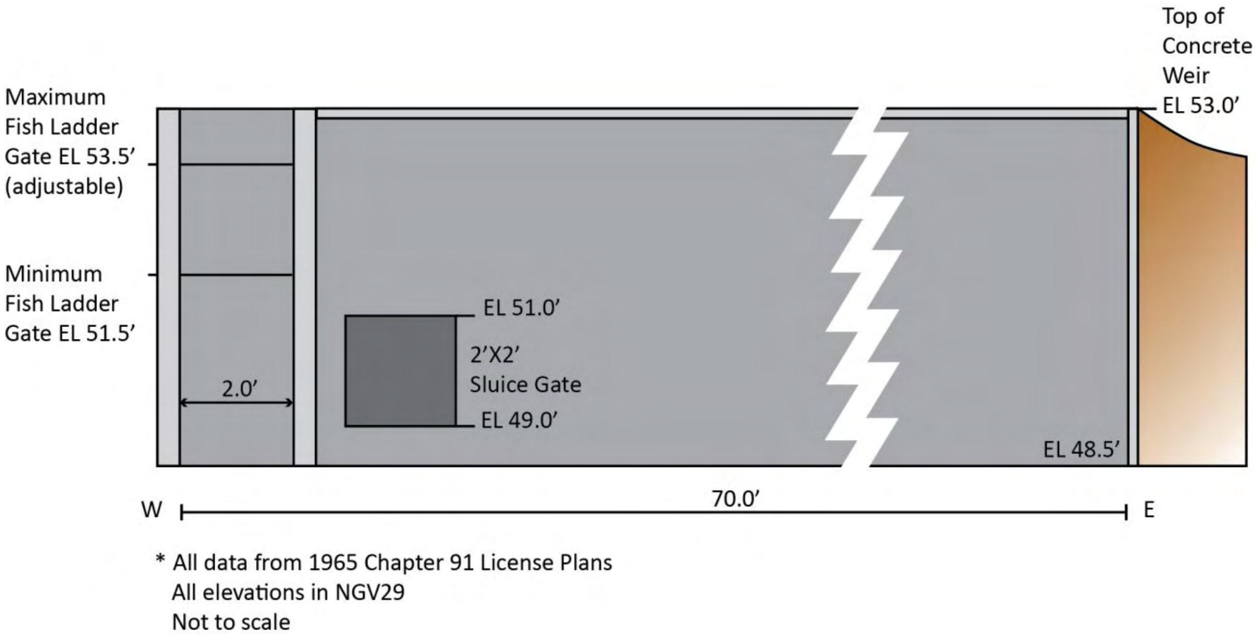
Figure 2. Monponsett Pond Water Management Features

Based upon the Chapter 91 license plans for the dam and a field inspection by HW personnel, Stump Brook can flow past the dam by three routes (Figure 3):

1. Over the primary spillway at the crest of the dam with an elevation of 53.0 feet NGVD29;
2. Through a fish ladder with a minimum invert elevation of 51.5 feet NGVD29 and an adjustable gate that allows the ladder to be closed up to a maximum invert elevation of 53.5 feet NGVD29; and
3. Through a two-foot by two-foot low-flow sluice opening with an invert elevation of 49.0 NGVD29 and a gate that can be adjusted between fully open and fully closed.

Figure 3 conceptually illustrates the Stump Brook Dam configuration. According to the Brockton Water Commission (BWC) and the MWA, the fish ladder is currently operated to be always open to allow fish to readily pass the spillway. The sluice gate can be opened to different heights but, according to the MWA, it currently is primarily maintained in the fully closed position.

Figure 3. Conceptual Cross-Section of Stump Brook Dam



Stump Brook Dam **Dam Controls**

We note that the MWA and the Jones River Watershed Association (JRWA), among others, have anecdotally reported another potentially negative consequence of the construction of the dam and the diversion pipe. The potential exists for the natural flow of water from east to west (to exit through Stump Brook) to reverse at times when large volumes of water are being diverted from East Pond. During such times, water may flow through the culvert from west to east to feed that diversion. Such a reversal of flow may also have water quality impacts as the water quality in West Pond is reportedly worse than that in East Pond. The prevalence of generally poor water quality in West Pond is supported by water quality sampling data (Princeton Hydro, 2013 and Lycott Environmental, 2014), and by the significant observed algal blooms and the occurrences of potentially toxic cyanobacteria blooms (MWA, MA Department of Public Health (DPH), and Halifax Board of Health (BOH)).

2.0 Objectives

The objectives of this study are to evaluate the potential of different scenarios of water supply management by BWC to increase flow through Stump Brook and to improve water quality in Monponsett Pond. This report is generally organized into two main sections representative of the two main study objectives. There are two primary options for changing how water supply is managed from Monponsett Pond:

1. Change the rate and/or timing of diversions from East Pond to Silver Lake; and
2. Change the Stump Brook Dam settings to allow more water to exit through Stump Brook.

This study utilized the United States Geological Survey (USGS) MODFLOW numerical groundwater flow model for the Tri-basin area (Carlson and Lyford, 2005) to conduct water budget analyses to inform both the flow and water quality assessments. MODFLOW (Harbaugh and others, 2000) is a three-dimensional groundwater flow model capable of simulating the complex flow dynamics within aquifers, and the interactions between groundwater and surface water. It is a finite difference model that calculates water levels and water budget components at georeferenced grid-specific locations (i.e. model cells) at specified time steps throughout its simulation period. MODFLOW is a powerful hydrogeologic tool that allows for different scenarios of water management and/or natural hydrologic variation to be evaluated comprehensively within its grid structure. As the hydrology of Monponsett Ponds and Stump Brook area is significantly influenced by groundwater interactions, MODFLOW is an effective tool to use to evaluate the implications of different water management scenarios.

The USGS groundwater model simulates the diversion of water from Monponsett Pond to Silver Lake by using 16 extraction wells distributed throughout East and West Ponds. The model wells in Monponsett Ponds remove water from the ponds and another set of model wells inject that water into Silver Lake to complete the simulated water diversion process. In this study, different diversion scenarios were relatively simple to evaluate by adjusting the withdrawal rates and schedules of those extraction wells. The Stump Brook Dam was not explicitly modeled by USGS and no simple dam feature is available in MODFLOW. Therefore, different dam management scenarios and their impacts on Stump Brook flow were evaluated by utilizing water budget outputs from the MODFLOW model to inform a spreadsheet evaluation of dam flow based on standard engineering calculations for flow through weirs representing the dam spillway, fish ladder, and low-flow sluice gate.

3.0 Groundwater Modeling

3.1 Groundwater Model Setup

HW obtained from USGS the MODFLOW input files necessary to reproduce the USGS groundwater model for the Tri-basin area. The USGS model was published as “Simulated Ground-Water Flow for a Pond-Dominated Aquifer System near Great Sandy Bottom Pond, Pembroke, Massachusetts” (Carlson and Lyford, 2005). Input files were obtained and used to reconstruct a steady-state model, a six-year transient model representing climactic conditions from 1998 through 2003, and a four-year transient model representing average monthly climatic conditions. Steady state models produce a single output representing long-term average conditions. Transient models include variable input factors for different “time steps” and produce outputs unique to those time-specific input variables.

HW began by importing the steady-state model into Groundwater Vistas (GWV), a graphical input and output visualization software package for MODFLOW. There were a number of changes that needed to be made to the USGS input files to make them usable in GWV, such as changing certain file extensions and routing package numbers, altering folder organization structure, and using a different numerical solver. Once we were able to get the steady-state model running, HW compared the simulated groundwater contours reported by GWV to the contours produced by the USGS model, as documented in Figure 8 of the USGS Tri-basin report (Carlson and Lyford, 2005). The results were essentially identical, with the HW model generated contours having slightly sharper edges than those depicted in the USGS report. This was perhaps a result of using different post-processing contouring packages. This first step provided the crucial confirmation that the MODFLOW input files obtained from USGS, and processed and run by HW using GWV, produced the same numerical results as those depicted by the USGS in Carlson and Lyford, 2005.

After confirming that the steady-state model was performing as expected, HW imported the 1998-2003 transient model into GWV, following the same steps as those utilized for the import of the steady-state model to ensure that the 1998-2003 transient model ran properly. The 1998-2003 model overlaps with the time period of available water level and diversion data and was, therefore, useful for model calibration to ensure that the model simulated conditions similar to those observed for discrete time steps in the field data record.

3.1.1 Description of the USGS Model

The USGS model simulates ground-water flow for a 66.4 square mile area around Great Sandy Bottom Pond near Pembroke, Massachusetts. Wetlands and ponds cover approximately 30 percent of the area in the model. The aquifer system is dominated by interactions between ground-water and the streams and ponds. Altitudes in the model area range from approximately 10 feet to 150 feet above the vertical datum NGVD 29. The USGS model has the following primary properties:

- Grid cells are 250 feet on edge, with the model domain comprised by a total of 185 rows and 205 columns;
- Three vertical layers are used to simulate the aquifer system, with layers 1 and 2 representing surficial materials and bedrock within 20 feet of land surface and layer 3 representing bedrock;
- Boundary conditions at the edge of the model are no-flow cells near ground-water divides and constant-head cells at certain surface water features;
- Hydraulic conductivity for aquifer materials varies between 10 feet/day and 80 feet/day, the ponds are set at 50,000 feet/day to represent the “open” water column, and wetland areas are set at 1,000 feet/day;
- Streamflow is simulated using the Streamflow Routing package (Prudic and others, 2004) which simulates streams as a head-dependent boundary condition capable of either gaining or losing water from or to the aquifer based upon the head differential between the stream cell and the adjacent aquifer cells;
- A total of 199 stream segments are used and simulated streams were assigned a width of 10 feet. Streams that entered and exited ponds are simulated as continuously flowing through the pond and streambed hydraulic conductivity is set to 3 feet/day;
- Simulated stresses include production wells, surface-water withdrawals and exports, and recharge. Monthly recharge rates account for precipitation, soil-moisture capacity, evapotranspiration, wastewater discharge to groundwater and pond evaporation.

Time is simulated in MODFLOW through the use of “stress periods” and “time steps”. Stress periods are time intervals of consistent hydrologic stress and time steps are the smaller units to which each stress period can be broken out. For example, groundwater recharge in the model is simulated with variable values that change by month. So each calendar year has 12 monthly stress periods within the model and the model calculates results for 12 time steps within each stress period. Three different models were created by USGS and used by HW for this study, as discussed in this report. They are:

- A steady-state model with no stress periods. This is the simplest of the models. It calculates output conditions for a single time reflective of long-term average conditions. It was used primarily as a first step to make sure that our import and use of the USGS model produced the same output results as those depicted in the USGS report (Carlson and Lyford, 2005).
- A six-year transient model that has 69 monthly stress periods representing January 1998 to September 2003. This model was used in this study to calibrate and compare the model to observed field data.
- A four-year transient model with 48 monthly stress periods representing January 1998 to December 2001. This model uses average monthly recharge conditions for each calendar month (based on 1949-2002 field data) that are repeated for each year (e.g. January year 1 has the same recharge value as January year 2) and 2002 pumping rates for all wells in the model. This model was used for the predictive simulations at the heart of this study.

3.1.2 HW Changes to the USGS Model

In order to better simulate the hydrologic and hydrogeologic conditions of the local Monponsett Pond and Stump Brook area for the specific purposes of this study, HW made a number of changes to model input parameters in the Monponsett Pond area:

- Changed the hydraulic conductivity of Monponsett Pond from 50,000 feet/day (USGS value) to 500,000 feet/day to better simulate the open connection and free flow of surface water. This change is reasonable given the unrestricted ability of water to move from one place to another in an open water body with no restriction from geologic materials. The change also allowed the Pond to maintain a relatively flat water surface despite the influence of the imaginary extraction wells used to simulate the diversion to Silver Lake. Previously, in the USGS model, "cones of depression" could be observed around the extraction wells when model output was viewed at a sufficiently fine contour interval.

- In an effort to better maintain a flat pond surface elevation, the original USGS model included stream cells running through the centers of all of the major ponds in the model domain. HW attempted to remove those stream cells from Monponsett Pond but their removal led to model instability that we were unable to effectively resolve. Therefore, the stream cells were retained in Monponsett Pond as originally simulated by USGS. However, with the order of magnitude increase of pond hydraulic conductivity (described above) the in-pond stream cells do not appear to be unduly influencing simulated conditions for the pond.

- The stream bed elevation and stage in the stream cells used to simulate Stump Brook between the pond and the dam were adjusted to reflect available field data and represent a slight hydraulic gradient change between the pond and the dam (consistent with field-survey conducted by Green Seal Environmental, Inc. in June 2015).

- To better simulate the limited culvert linkage between East Pond and West Pond, the bottom elevation of the stream cell connecting the two ponds was changed from 39 feet to 51 feet reflecting actual site conditions. This change was enacted to allow the two ponds to separate in the event that simulated pond levels dropped below the invert of the connecting culvert; as would occur in reality.

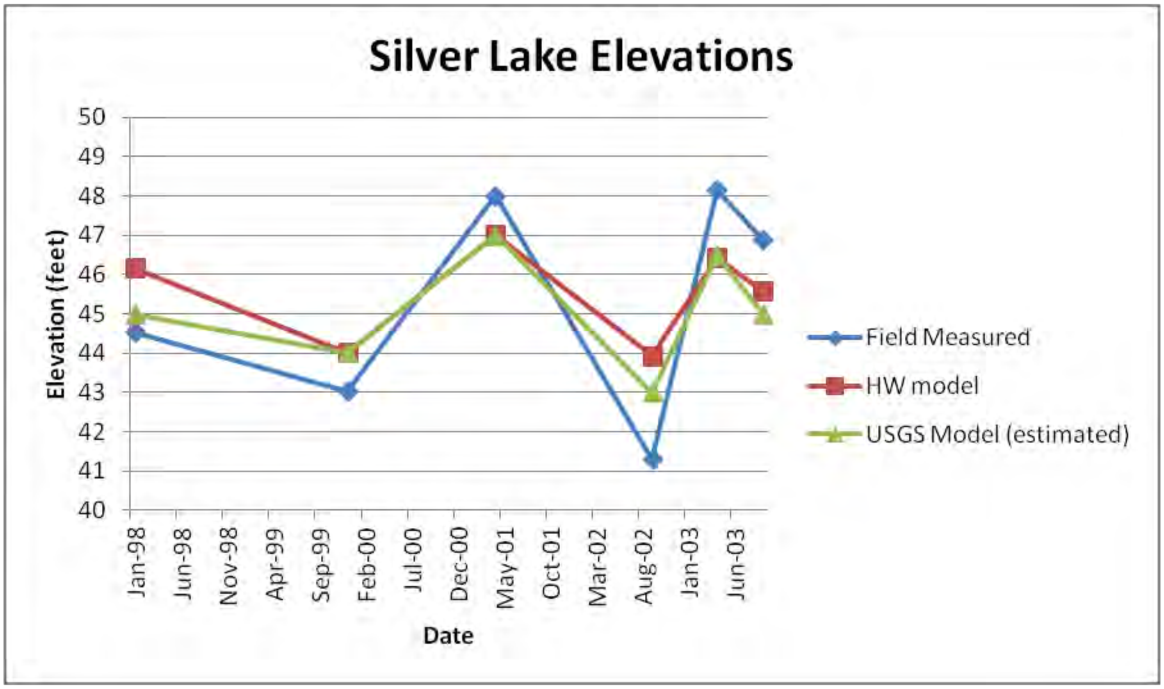
- The entire diversion to Silver Lake was simulated solely with wells located in East Pond in order to more realistically simulate the actual location of the diversion pipe in the southeast corner of East Monponsett Pond.

3.1.3 Model Calibration

While the model was previously calibrated by the USGS to be regionally accurate over the entire model domain, HW undertook additional calibration to verify that the HW-revised model (see Section 3.1.2) did not appreciably detract from the reported USGS calibration, and to better understand the accuracy of the revised model for this study's focus area around Monponsett Pond. HW compared the HW 1998-2003 model-simulated Silver Lake and Monponsett Pond elevations, to those computed by the original 1998-2003 USGS model and to those measured and reported by the Brockton Water Commission. HW selected 5 months during the 6-year period, representing both wet and dry periods, to compare HW-modeled values to the expected values from the USGS model and field measurements.

HW compared Silver Lake elevations to USGS-modeled Silver Lake elevations (approximated from Figure 7 from the USGS report) and BWC field measured values (Figure 4). With the exception of the first time step in the model, the HW and USGS models produce nearly identical values, as one would expect. What small discrepancies are observed are likely due to the inaccuracy of visually transcribing USGS values from the graphs presented in the report (Carlson and Lyford, 2005). The variance observed for the initial time step in January 1998 may have to do with the starting heads used for the model and insufficient elapsed time having passed to allow the model to better refine. USGS and HW modeled elevations are both within the range of the values reported by BWC, but do not seem to entirely capture the high and low fluctuations.

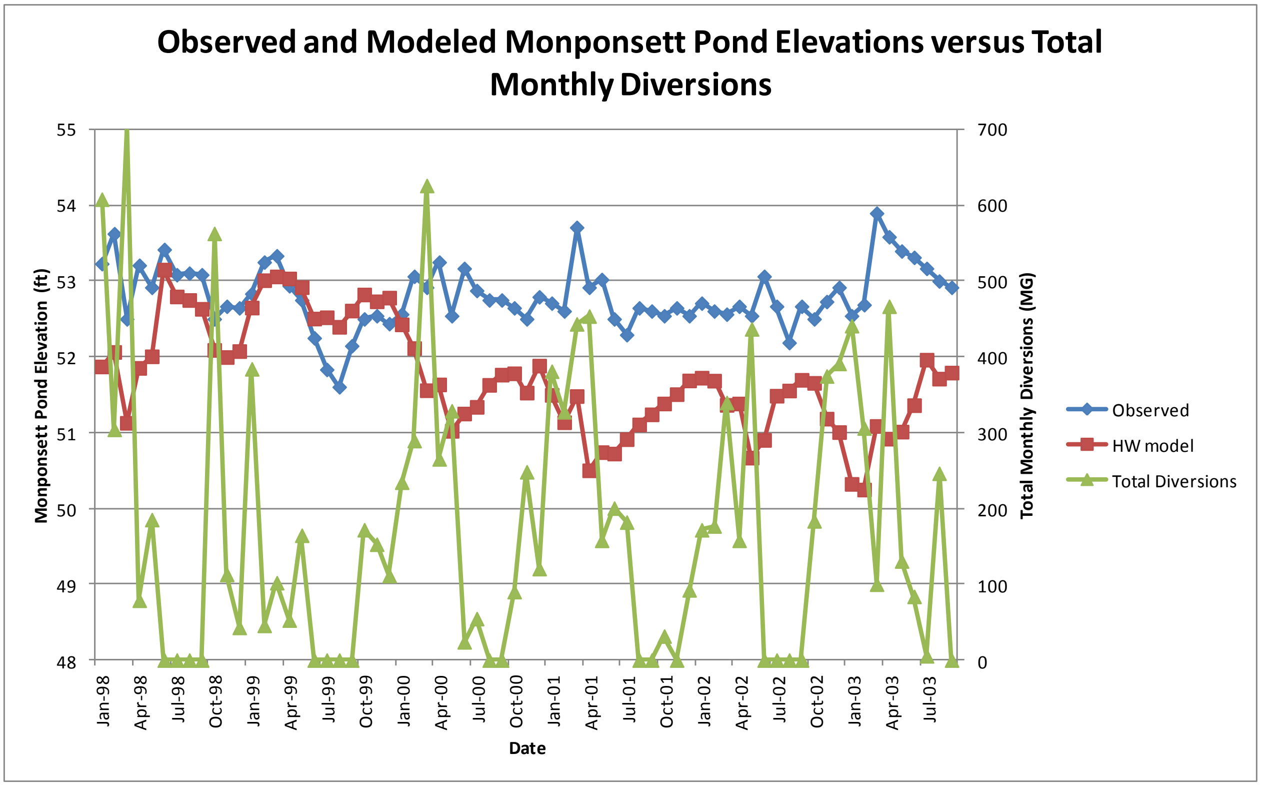
Figure 4. Comparison of Modeled to Observed Silver Lake Elevations



The USGS report did not include Monponsett Pond elevations, so HW compared the HW-modeled Monponsett Pond elevations to field measurements provided by BWC (Figure 5). The BWC reports the Monponsett Pond elevation as inches over a datum near the diversion intake structure in East Pond. The BWC datum is at 52.5 feet NGVD29. BWC measurements can be easily converted to NGVD29 elevations by simply converting inches to feet and then adding (or subtracting, as appropriate) from the datum elevation. Figure 5 also includes the total BWC diversions from Monponsett Pond by month in order to show how the model responds to the diversions.

As can be seen from Figure 5, the model-simulated pond elevations are a fairly close match to the BWC-measured pond elevations from 1998 to early 2000. In particular, the time period between approximately July of 1998 and February of 2000 illustrates a good match between modeled and observed pond elevations. Importantly, that time period, is also marked by the lowest diversion volumes over the modeled time period. Following a large diversion volume of over 600 MG in March of 2000, the modeled pond elevations begin to decline below the observed elevations and then never recovers for the remainder of the modeled time period as subsequent diversions deplete the pond storage before it can recover from the last diversion period. Modeled pond elevations fluctuate from one to two feet below the observed pond elevations over that time period.

Figure 5. Comparison of Modeled to Observed Monponsett Pond Elevations and Total Monthly Diversion Volumes



The response pattern illustrated in Figure 5 shows that the modeled pond is more responsive to large diversions than is the actual pond. This indicates that the real world pond receives additional recharge to replenish its volume beyond that which is simulated by the model. The greater resilience of the real world pond to diversions (compared to the modeled pond) likely occurs because as the pond level drops in response to diversions, groundwater flow into the pond increases to partially offset that diversion volume. All else being equal, groundwater flow increases as the hydraulic gradient in the aquifer steepens. If you lower the pond elevation while the aquifer head upgradient in the watershed stays the same then the gradient increases and the groundwater flow into the pond increases.

If the diversions continued indefinitely, the upgradient aquifer heads would also drop in response to the diversion outflow, reducing the gradient, and diminishing the groundwater inflow. A new equilibrium condition would be reached with a lower pond elevation. Based on Figure 5, it looks like, at least over this modeled time period, the off-period for diversions combined with adequate precipitation-based recharge to the aquifer is enough to prevent the real world pond from falling to a new, lower equilibrium position. The fact that the modeled pond is less resilient than the real world pond indicates that, relative to the model simulation, the real world conditions must have some combination of higher aquifer recharge to the watershed than is modeled, higher storage in the aquifer than is modeled, higher conductivity of the aquifer than is modeled, and/or a larger storage volume in the pond than is modeled.

While we did increase the hydraulic conductivity of the pond itself for our model relative to the USGS model, it was beyond our Scope of Work to make wholesale changes to the USGS model for broad areas surrounding the pond. The model domain is much larger than the Monponsett Ponds area and changes to the aquifer characteristics of different geologic materials would have broad implications across the entire model domain. In addition, because the USGS model includes geospatial representation of mixed precipitation-based recharge and septic system recharge, it would be very difficult to accurately increase only precipitation-based recharge for specific model cells. For these reasons we did not alter the USGS model representation of aquifer properties in an effort to improve the model calibration to observed Monponsett Pond elevations. No additional changes were made to the model beyond those discussed in Section 3.1.2.

Despite the overall poor match of observed to simulated pond elevations, we do note that the average discrepancy between simulated vs. observed changes in Monponsett Pond elevation between any two representative time steps is approximately 0.3 feet. This is a relatively reasonable discrepancy that lends confidence to the ability of the model to adequately assess the influence of various management scenarios on pond level changes. So while the model appears to generally underpredict the absolute value of Monponsett Pond elevation at any given time, the simulated change of pond elevation in response to simulated stressors seems reasonable.

For the purposes of this study, streamflow is also an important calibration component. Unfortunately, there are no available, reliable measurements of total flow in Stump Brook at the dam. There are calculated flows for the fish ladder component alone based on as unpublished stage/discharge relationship of unknown accuracy (Gomez and Sullivan, 2014), but no measured total flows. Another potential source of data comparison is the USGS sustainable yield estimator (SYE) values based upon GIS correlation to other, similar, gauged streams. However, given the major diversions from Monponsett Pond, the impacts of the dam, and other upstream anthropogenic factors (e.g. cranberry farming), it is uncertain how accurate SYE flow estimates may actually be. The influence of anthropogenic alterations affecting Stump brook flow may outweigh watershed size and the other natural factors which the SYE uses for comparisons of ungauged to gauged streams.

HW computed monthly average stream flows for the segment of Stump Brook downstream of the dam form the 1998-2003 USGS Model. Model-computed Stump Brook flows are similar to the measured fish ladder flows for 2013-2014 (Table 1) and much less than SYE estimated flows. While both the SYE flows and fish ladder measurements may be inaccurate to varying degrees, the fish ladder measurements have the benefit of at least being based upon actual field measurements over a time period where we understand the fish ladder to have been maintained as open (MPA personal communication). The SYE estimated flows are approximately an order of magnitude higher than either the measured fish ladder flows or the model-simulated flows.

Please note that the fish ladder flow estimate data covers the time period from January to December 2013, and from March to September 2014, while the 1998-2003 USGS Model obviously simulates an earlier time period. For this reason, a direct calibration comparison cannot be made between modeled stream flow and estimates of flow through the fish ladder. However, based on BWC data, average precipitation over the 2013 and 2014 time period was 0.15 inches per day and the average precipitation for the 1998-2003 time period was 0.16 inches per day. Therefore, hydrologic conditions appear to have been roughly similar between the two time periods. As shown in Table 1, the average monthly Stump Brook flows from the groundwater model are in general agreement with the estimated flows through the fish ladder.

Table 1. Comparison of Average Monthly Model Calculated Stump Brook Flow and Flow Measured through the Fish Ladder

Month	Stump Brook Flow (cfs)	Stump Brook Flow (MGD)	Fish ladder flow (cfs)	Fish ladder flow (MGD)
1	1.82	1.18	0.60	0.39
2	2.10	1.36	2.08	1.34
3	2.31	1.49	5.16	3.34
4	1.58	1.02	2.29	1.48
5	1.15	0.74	3.33	2.15
6	1.45	0.94	4.40	2.84
7	0.83	0.53	3.67	2.37
8	0.70	0.46	2.62	1.69
9	0.68	0.44	0.98	0.64
10	0.82	0.53	0.78	0.51
11	0.84	0.54	0.81	0.52
12	1.09	0.70	2.97	1.92
Total	**15.35**	**9.92**	**29.70**	**19.19**
Average	**1.28**	**0.83**	**2.47**	**1.60**

As discussed regarding calibration to Monponsett Pond elevation, it also appears that (while not always a great absolute match) the model generally simulates the change in flow between time steps and, as such, can be a useful tool for evaluating the potential impacts of different management scenarios.

3.1.4 Average Conditions Model

For predictive simulations conducted to assess potential hydrologic changes resulting from alternative water management strategies, HW used the 4-year transient USGS model that includes average monthly recharge conditions for each calendar month (based on 1949-2002 field data) that are repeated for each year (e.g. January year 1 has the same recharge value as January year 2) and 2002 pumping rates for all wells, withdrawals, and exports in the model. This includes the Monponsett Pond extraction wells used to simulate the diversions to Silver Lake. In the average conditions model those wells divert water as occurred during 2002. Total 2002 diversions from Monponsett Pond approximate the average annual diversion volume over the time period from 1996-2014 (Table 2). Because of the close match between 2002 and average diversions, HW decided not to alter the USGS use of 2002 pumping rates for this model.

The average conditions model contains all the same HW alterations to the local Monponsett Pond area described above for the 1998-2003 model. The average conditions model was not explicitly calibrated to any field data because the calibration was already conducted for the 1998-2003 model, and because there are no time-specific field data to compare against the average conditions simulated by the model.

Table 2. Comparison of Observed and Model Total MP Diversions (MG)

Month	Average 1996-2014 Diversions (MG)	Min 1996-2014 Diversions (MG)	Max 1996-2014 Diversions (MG)	2002 Model Diversions (MG)
				2002
1	365.5	129.4	747.6	172.0
2	308.4	45.7	657.2	177.0
3	439.3	59.8	711.8	340.0
4	307.7	0.2	657.8	158.0
5	234.2	37.6	436.8	437.0
6	95.3	0.0	455.4	0.0
7	26.5	0.0	182.0	0.0
8	14.5	0.0	246.4	0.0
9	19.6	0.0	302.6	0.0
10	144.5	0.0	562.8	184.0
11	161.8	0.0	416.1	375.0
12	271.6	0.0	771.5	391.0
Total	2388.9	1185.6	3690.4	2234.0

3.1.5 Alternative Water Management Scenarios

The objectives of the groundwater modeling for this study were to evaluate the estimated changes to Monponsett Pond water level and Stump Brook flow resulting from varying water management scenarios. In collaboration with DER staff, HW evaluated the hydrologic impacts from the following water management approaches in the average conditions MODLFOW model:

1. Average conditions (e.g., average recharge and diversions);

2. No diversions from Monponsett Pond to Silver Lake;

3. Diversions within the allowed operating period (i.e. October – May) only as needed (i.e., when the elevation of Silver Lake is below its dam spillway elevation); and

4. Various configurations of the low-flow sluice gate opening at the Stump Brook dam (per MWA information regarding current conditions, all scenarios include the fish ladder fully open).

Based on combinations of the above diversion and dam management options, HW simulated nine scenarios that are included in this report:

1. 2002 average monthly diversion conditions with Stump Brook spillway sluice gate closed;
2. 2002 average monthly diversion conditions with Stump Brook spillway sluice gate open;
3. 2002 average monthly diversion conditions with Stump Brook spillway sluice gate half-open;
4. No diversions occurring with Stump Brook spillway sluice gate closed
5. No diversions occurring with Stump Brook spillway sluice gate open;
6. No diversions occurring with Stump Brook spillway sluice gate half-open;
7. Diversion occurring as-needed with Stump Brook spillway sluice gate closed;
8. Diversion occurring as-needed with Stump Brook spillway sluice gate open; and
9. Diversion occurring as-needed with Stump Brook spillway sluice gate half-open;

Diversion scenarios were simulated in the model by varying the pumping rate of the eight model extraction wells in East Pond (Table 3). The as-needed scenario represents only diversions from Monponsett Pond that occur during the allowed diversion period (October to May), and when the Silver Lake elevation is below the spillway elevation of Silver Lake's outlet (Forge Pond Dam) so it could accept and store that water. To create this scenario, HW received data from DER that reported nineteen years of data for the average volume of diversions to Silver Lake during the months October – May that occurred when Silver Lake was below its spillway elevation. These averages are the total average as-needed diversion volume for each month divided by the total days in each month; not just the days when as-needed diversions occurred. This was done because the model uses a monthly time step.

Table 3. Average Daily Well Pumping Rates to Simulate Diversions from Monponsett Pond

	Monponsett Pond Diversions (cfs)			Monponsett Pond Diversions (MGD)		
Month	**2002 Diversions**	**No Diversions**	**Average Diversions**	**2002 Diversions**	**No Diversions**	**Average Diversions**
1	8.59	0	10.71	5.55	0	6.92
2	9.78	0	9.04	6.32	0	5.84
3	16.97	0	5.52	10.97	0	3.57
4	8.15	0	1.70	5.27	0	1.10
5	21.81	0	4.80	14.10	0	3.10
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	9.18	0	7.58	5.94	0	4.90
11	19.34	0	8.25	12.50	0	5.33
12	19.52	0	9.96	12.61	0	6.44
Total	113.34	0	57.56	73.25	0	37.20
Year Average	9.45	0	4.80	6.10	0	3.10

The three different diversion scenarios were evaluated with the average conditions MODFLOW model by adjusting the withdrawal rates and schedules of the extraction wells used to simulate the diversion (Table 3). For each scenario the model calculated Monponsett Pond elevation and water budget inputs and outputs for each monthly time step over the four-year simulation period. The Stump Brook Dam was not explicitly modeled by USGS and no simple dam feature is available in MODFLOW. Therefore, the different dam management scenarios and their impacts on Stump Brook flow were evaluated by utilizing the water budget outputs from the MODFLOW model to inform a spreadsheet evaluation of dam flow based on standard engineering calculations for flow through weirs representing the dam spillway, fish ladder, and low-flow sluice gate.

The Stump Brook Dam spreadsheet interacts with the average conditions MODFLOW model in an iterative fashion to estimate Stump Brook flows, and Monponsett Pond elevation for each day of a hypothetical, average condition year as follows:

1. A starting Monponsett Pond elevation of 52.82 feet was used for all the stage-storage spreadsheets. This was calculated as the average January elevation based on observed data from 1996-2014 from the Brockton Water Commission.

2. MODFLOW mass balance inflows and outflows from a hydrostratigraphic unit created by HW around Monponsett Pond are used in concert with a Monponsett Pond stage-storage relationship (Princeton Hydro, 2013) (Table 4) to estimate the change in pond elevation for each model time step.

3. The pond elevation from step 2 informed the spreadsheet calculation of flows through the three components of the dam (spillway, fish ladder, and low-flow sluice gate). For the purposes of the predictive spreadsheet, the spillway was modeled as an un-contracted horizontal weir, the fish ladder was modeled as a contracted horizontal weir since the fish ladder does not extend across the entire width of the channel, and the sluice gate was modeled as a weir /orifice (depending upon whether or not the top of the sluice gate was fully submerged) and assumed to have free-discharge.

4. The calculated flows through the dam were added to the non-streamflow MODFLOW mass balance components (see Equation 1) of the next time step to calculate the pond stage for the next time step. The process was then repeated over again. MODFLOW estimated streamflow was subtracted out of the equation because variation of Stump Brook flow by dam management scenarios was the key variable evaluated through this exercise and MODFLOW could not simulate dam management variation.

Equation 1.

Total Flow Out of Monponsett Pond = Total Inflows – [(Total Outflows – HSU #5 Stream Outflow – HSU #4 Inflow to HSU #5) + Flow through Sluice Gate + Flow through Fish Ladder]

Where:

- Total Inflows = MODFLOW total inflow to Monponsett Pond
- Total Outflows = MODFLOW total outflow from Monponsett Pond
- HSU #5 Stream Outflow = MODFLOW stream flow downstream of the dam
- HSU #4 Inflow to HSU #5 = MODFLOW stream flow from upstream of the dam conveyed to downstream of the dam
- Flow Through Sluice Gate = calculated flow using the predictive spreadsheet
- Flow Through Fish Ladder = calculated flow through fish ladder using the predictive spreadsheet

Table 4. Monponsett Pond Stage-Storage Calculation Data

Monponsett Pond Stage-Storage Data	
Elevation (ft)	**Volume (MG)**
53	1227.81
52	1044.77
51	871.98
50	709.88
49	559.42
48	421.26
47	304.1
46	210.25
45	133.53
44	71.9
43	25.59
42	4.48
41	0.02
40	0

3.2 Modeling Results

3.2.1 Diversion Scenarios

Data was exported for each of the Average Conditions Model scenarios to estimate changes in Monponsett Pond elevation (Table 5) and flow downstream of the Stump Brook Dam (Table 6) predicted to result from different diversion scenarios. All diversion scenarios in Tables 5 and 6 include our understanding of the current Stump Brook Dam operation (i.e. sluice gate fully closed and fish ladder fully open). Stump Brook flow downstream of the dam was estimated in the model by taking the model's mass balance output for streamflow for the segment of stream immediately downstream of the dam and then adding to it the model-computed mass balance transfer from the stream segment upstream of the dam to the segment downstream of the dam.

Table 5. Modeled Monponsett Pond Elevation by Scenario

Monponsett Pond Elevation (feet)			
Month	2002 Diversions	No Diversion	As-needed Diversion
1	50.62	52.69	52.04
2	50.69	52.79	51.99
3	50.63	52.87	52.04
4	50.59	52.91	52.16
5	50.33	52.85	52.16
6	50.12	52.73	52.12
7	50.25	52.60	52.10
8	50.33	52.49	52.09
9	50.41	52.44	52.10
10	50.41	52.43	52.07
11	50.14	52.48	51.99
12	49.72	52.58	51.93
Average	50.35	52.65	52.07

Note: As described in Section 3.1.3, modeled pond elevations are likely an underestimate.

Table 6. Modeled Stump Brook Flow from Monponsett Pond by Scenario

Stump Brook Flow (cfs)				Stump Brook Flow (MGD)		
Month	2002 Diversions	No Diversion	As-needed Diversion	2002 Diversions	No Diversion	As-needed Diversion
1	1.68	1.78	1.76	1.09	1.15	1.14
2	1.86	1.96	1.94	1.20	1.27	1.26
3	1.90	2.01	1.99	1.23	1.30	1.29
4	1.61	1.72	1.70	1.04	1.11	1.10
5	1.18	1.29	1.27	0.77	0.83	0.82
6	0.97	1.08	1.06	0.62	0.70	0.68
7	0.80	0.91	0.89	0.52	0.59	0.57
8	0.76	0.85	0.84	0.49	0.55	0.54
9	0.72	0.82	0.81	0.47	0.53	0.52
10	0.82	0.93	0.91	0.53	0.60	0.59
11	1.08	1.20	1.18	0.70	0.77	0.76
12	1.53	1.68	1.66	0.99	1.08	1.07
Total	14.92	16.23	16.01	9.65	10.49	10.34
Average	1.24	1.35	1.33	0.80	0.87	0.86

The model results indicate that significant increases in pond elevation may occur under the no diversions and as-needed scenario conditions as compared to the existing, or 2002 diversion, conditions. This is not surprising when considering that total annual diversions have averaged approximately two billion gallons per year over the 1998-2003 time period of BWC data reviewed for the model. Lesser increases in Stump Brook flow are simulated for the two alternative management scenarios, likely due to the fact that the low-flow sluice gate remained closed during these scenarios and the pond elevation remained below the spillway so that all stream flow exited through the relatively small fish ladder opening.

3.2.2 Dam Management Scenarios

The results from the predictive stage-storage calculation spreadsheets show the Monponsett Pond elevation and flow in Stump Brook due to the combination of dam management options and diversion scenarios (Table 7, Figure 6, and Figure 7). Table 7 presents results in terms of pond elevation at the end of each month and days required for the stream stage to drop below the inlets of the fish ladder and the low-flow sluice gate. For the purposes of these dam management scenario evaluations, Stump Brook flow was calculated by summing the flow through the sluice gate and the flow through the fish ladder. To our knowledge, flow has not gone over the top of the dam spillway over this study's model simulation time period.

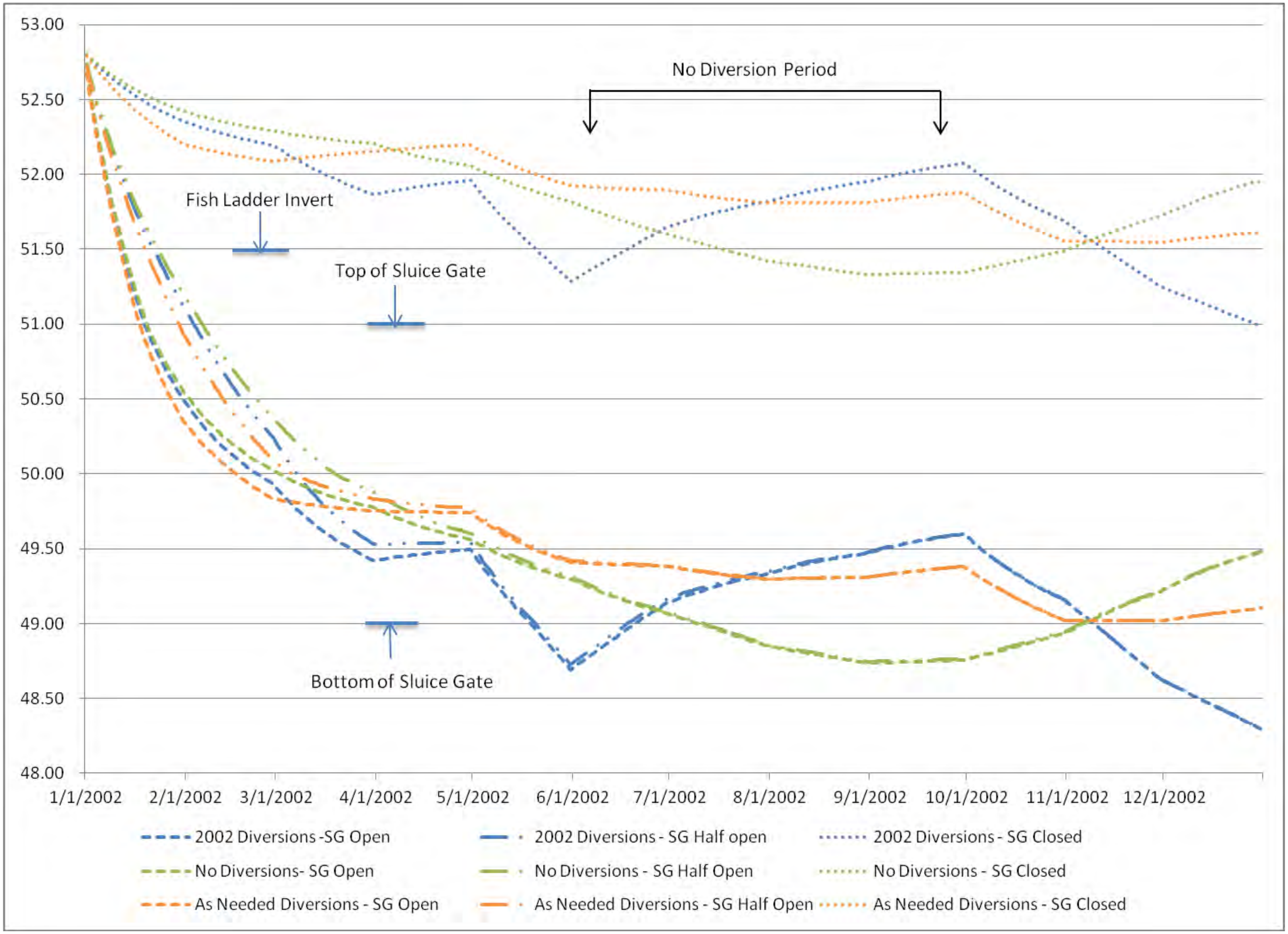
Figures 6 and 7, respectively, graphically depict the modeled changes in pond elevation and in Stump Brook Flow for the various combinations of dam management and diversion scenarios.

Table 7. Results from the Sluice Gate (SG) Scenarios

	2002 Diversions			No Diversions			As-needed Diversions		
	SG Open	SG ½ open	SG Closed	SG Open	SG ½ open	SG Closed	SG Open	SG ½ open	SG Closed
Days before no fish ladder flow	13	22	141	13	24	199	12	20	Always flow
Days before no flow through sluice gate	139	141	NA	191	193	NA	Always flow	Always flow	NA
End of year pond Elevation	48.30	48.30	50.98	49.48	49.48	51.96	49.10	49.10	51.61
Average pond elevation	49.45	49.56	51.82	49.46	49.57	51.83	49.58	49.67	51.93

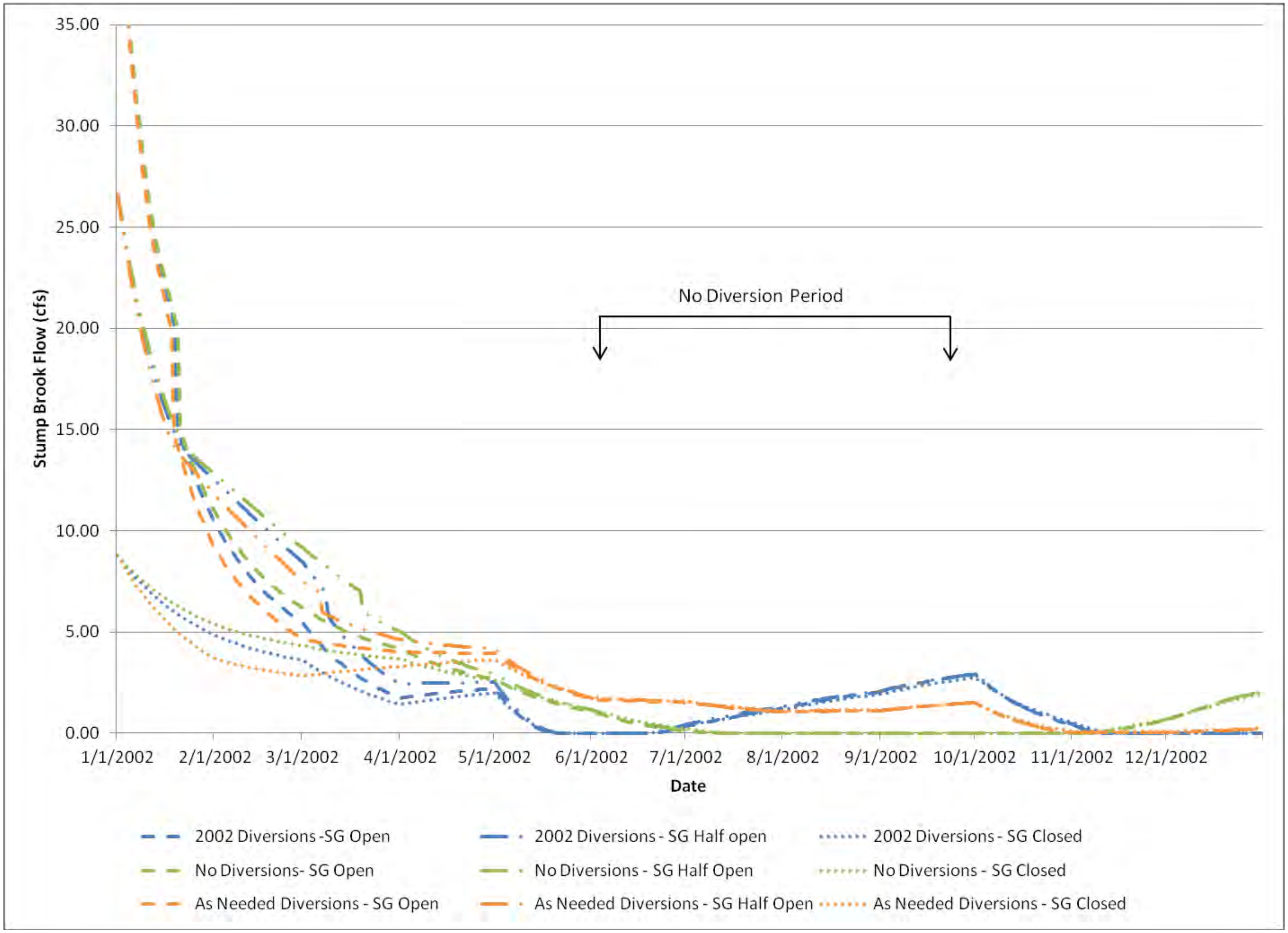
Note: As described in Section 3.1.3, modeled pond elevations are likely an underestimate.

Figure 6. Monponsett Pond Elevations as a Result of Sluice Gate Operation



Note: As described in Section 3.1.3, modeled pond elevations are likely an underestimate

Figure 7. Stump Brook Flow (cfs) as a Result of Sluice Gate Operation



The following are some key observations regarding Table 7 and Figures 6 and 7:

- The low flow sluice gate is calculated to be able to convey significant volumes of water and, as a result, significantly impact both pond level and Stump Brook flow. When the sluice gate is closed, flow through the fish ladder is sustained for longer periods of time, if not for the entire duration of the year. During the 2002 diversions scenario when the low-flow sluice gate is completely open, it takes only 13 days until there is no more flow through the fish ladder, and 139 days until the water level upstream of the dam is less than the invert of the low-flow sluice gate so that no flow through the sluice gate occurs.

- During the as-needed diversions, when the sluice gate is open fully, it takes 12 days until there is no more flow through the fish ladder. Flow through the sluice gate is continuous for the duration of the year.

- On Figure 6 it can be seen that at the begin of the simulation year all of the fully open sluice gate options draw the pond down faster than the half open gate options. Once the pond level drops below the top of the sluice gate, the rate of flow out of the sluice gate slows and the rate of pond drawdown also slows as a consequence. As time progresses and the pond elevation drops closer to the bottom of the sluice gate, the rate of flow through the sluice gate continues to drop until the influence of diversions becomes more significant than the influence of flow through the sluice gate. At this point pond levels under the 2002 diversion scenarios drop far below pond levels under either the no diversion or the as-needed diversion scenarios.

- During the no diversions allowed summer period, pond levels under the 2002 diversions scenario are simulated to rebound back to levels that are actually higher than those simulated for the no diversion or as-needed diversions scenarios. Examination of the detailed MODFLOW water budget files reveals a likely explanation for this phenomenon. Under diversion scenarios, and most notably the 2002 diversions scenario, the simulated pond water budget is dominated by the diversion exports. In order to balance the diversion outputs from the pond's water budget, MODFLOW simulates significant reductions in streamflow outputs and significant increases in the contributions from groundwater storage. When the no-diversion summer period is reached, those compensating water budget components actually create a condition when inputs to the simulated pond water budget are greater than outputs and, as a result, pond levels are simulated to rise.

- The fact that simulated water budget inputs are greater than outputs during the summer period when water levels are typically dropping indicates that this phenomenon may be more of a model-generated occurrence than something that may really occur. At the very least, water contributed from aquifer storage is a temporary addition that must be made up for at some later time. It is unlikely that this simulated temporary rebound of pond levels in the summertime would be likely to occur over long-term average conditions. To this point, it is noted that after diversions commence anew in November, pond levels under the 2002 diversions scenarios are simulated to drop sharply again for the remainder of the simulation year. If the simulation continued to run for longer than a year it is unlikely that simulated pond levels would be able to return to the same elevations simulated for the first spring of the simulation year.

- Figure 7 exhibits similar patterns for streamflow as those discussed above for pond levels.

3.3 Modeling Conclusions

The results from both the Average Conditions model diversion scenarios and the stage-storage calculation spreadsheet show that with management of the diversions to Silver Lake and the Stump Brook dam, flow in Stump Brook and Monponsett Ponds elevations can both be varied to a significant extent.

Comparing the year-end elevation in the stage-storage calculation spreadsheets to the average annual elevation values from the average-conditions MODFLOW model in the same scenario, one can evaluate how the dam management scenario is predicted to change pond elevation in one year (Table 8). The percent changes in pond elevation for scenarios with no or as-needed diversions are greater than those scenarios with 2002 diversions because the average annual modeled pond elevation is higher for the no or as-needed diversion scenarios. Since the pond is modeled to start at a higher elevation for those lower diversion scenarios, dam management is able to draw the pond down further. In all cases, it appears that dam management should be capable of significantly lowering pond elevation and, as a corollary, increasing Stump Brook flow.

Table 8. Percent Change in Monponsett Pond Elevation due to Sluice Gate (SG) Management

	2002 Diversions		No Diversions		As-needed Diversions	
	SG Open	SG Half-open	SG Open	SG Half-open	SG Open	SG Half-open
Model average annual elevation	50.35	50.35	52.65	52.65	52.26	52.26
Stage-storage calculated average annual elevation	49.45	49.56	49.46	49.57	49.58	49.67
Percent change in elevation	-1.8%	-1.6%	-6.1%	-5.9%	-5.1%	-5.0%
Percent change in pond depth	-13.9%	-12.2%	-49.2%	-47.5%	-41.2%	-39.8%

Note: As described in Section 3.1.3, modeled pond elevations are likely an underestimate.

* An average pond depth of 6.5 feet was used (Princeton Hydro, 2013).

It should be remembered however, as described in Section 3.1.3, that the modeling conducted in this study likely over predicts the amount of pond drawdown likely to occur during any scenario. This is because the model seems to underestimate the ability of groundwater inflow to compensate for pond losses as the groundwater gradient steepens in response to lowered pond elevations, at least over relatively short time periods. This is likely also true for the spreadsheet calculations for flow through the Stump Brook Dam. Those calculations show fairly significant drawdowns in pond stage that occur relatively quickly in response to openings of the low-flow sluice gate. Actual pond drawdowns will likely occur slower and to a lesser magnitude due to increases in groundwater inflow that will tend to offset the increased flow through the dam, at least over relatively short durations of time. As a point of comparison to illustrate the likely over prediction of pond level drawdown from dam management, BWC opened the sluice gate wide open from April 7 to May 8, 2015 at a time when no diversions were occurring and the pond stage was observed to drop by approximately 0.65 feet over that month. In contrast, the spreadsheet dam flow calculations discussed here for this study predict an approximately two-foot drop of pond level over the first month of a wide open sluice gate; more than double what was observed in the spring of 2015. This indicates that, at least in the short term, pond levels are unlikely to fall as quickly as the modeling and calculations in this study suggest.

Over long time periods, Monponsett Pond, Stump Brook, and the surrounding aquifer all will come into equilibrium with the prevailing long term average conditions of aquifer recharge, diversions, and dam outflow. All else remaining equal, increasing dam outflow will result in overall lower pond elevations as a long term average condition. Streamflow will increase in the short term as dam outflow increases, but then revert to long term average conditions as the system regains balance between all of its inflows and outflows.

On this point, it is illustrative that the total calculated flow through an open low-flow sluice gate on an annual basis is approximately half of the typical annual BWC annual diversions to Silver Lake. Despite this fact, the model and spreadsheet calculations in this study predict more substantial drawdowns of pond elevation than have been observed to occur as a result of the ongoing diversions. Again, at least over relatively short time periods, the real world pond appears to be more resilient to water losses than this study's model and calculations predict. If pond elevations remained higher than simulated, the low-flow sluice gate would be capable of transmitting more water over a longer time period than estimated here because the pond elevation would remain above the invert of the sluice gate for a longer period of time.

While the modeling and calculations conducted in this study cannot predict the exact changes in stream flow and pond elevation that may result from different management scenarios of diversions and/or the dam, they do suggest that, relatively speaking, the existing dam infrastructure appears capable of transmitting significantly more flow downstream if the low-flow sluice gate were operated in the open or partially open positions for longer periods of time than currently occurs. If increased flow through the dam were timed to occur during periods of no or minimized diversions (following the as-needed diversion concept of only diverting water when Silver Lake has capacity to accept it), Stump Brook flow might be increased without necessarily reducing pond elevations to undesirable levels. Such a change in water management should be conducted carefully and monitored closely to observe how the system responds and allow for the gate to be closed if pond drawdown is observed to occur more rapidly or to greater extent than desired.

The most prudent course of action would likely be to experiment with opening the sluice gate in small increments for limited time periods and observing the impacts on pond stage and stream flow. While only fully open and half open sluice gate positions were evaluated in this study, it is our understanding that the gate is fully adjustable over smaller increments. Incremental, monitored dam management, conducted in concert with a known diversion schedule, should be effective at evaluating optimum settings to enhance stream flow without unduly reducing pond levels.

3.4 Model Limitations

The work presented in this document provides an estimate of the relative hydrologic effects of the Monponsett Pond diversions and Stump Brook Dam management alternatives. All assessments are based on the use of a USGS regional MODFLOW model of the greater Tri-Basin area. The results of the groundwater simulations represent the best information available at this time but should not be considered absolutely accurate at any specific location or time. Although model simulation results are approximate by nature, the relative comparison of different modeled scenarios does provide adequate information to evaluate the relative changes in Monponsett Pond elevation and flow in Stump Brook due to variations in the volume of water diverted to Silver Lake and regulated by the Stump Brook dam.

4.0 Water Quality Modeling Evaluation

The purpose of modeling the water quality in Monponsett Pond is to estimate the effect of various water management alternatives (described above) on pond water quality through flow augmentation and nutrient load reduction.

4.1 Description of Pond Watershed

4.1.1 Pond Characteristics

A summary of Monponsett Pond characteristics are given in Table 9.

Table 9. Monponsett Pond Characteristics

Parameter	Units	West Pond	East Pond
Lake Area[1]	ha	124.98	110.03
	acres	308.83	271.88
Watershed[2]	ha	611.77	892.29
	acres	1511.69	2204.85
Average Depth[3]	m	2.09	1.84
	feet	6.84	6.04
Maximum Depth[3]	m	3.96	3.96
	feet	13.00	13.00
Lake Volume at Max. Depth[3]	Mm3	2.61	2.04
	MG	689.55	537.78

[1] MassGIS NHD Water Body

[2] Delineated in this report (HW, 2015)

[3] Princeton Hydro (2013)

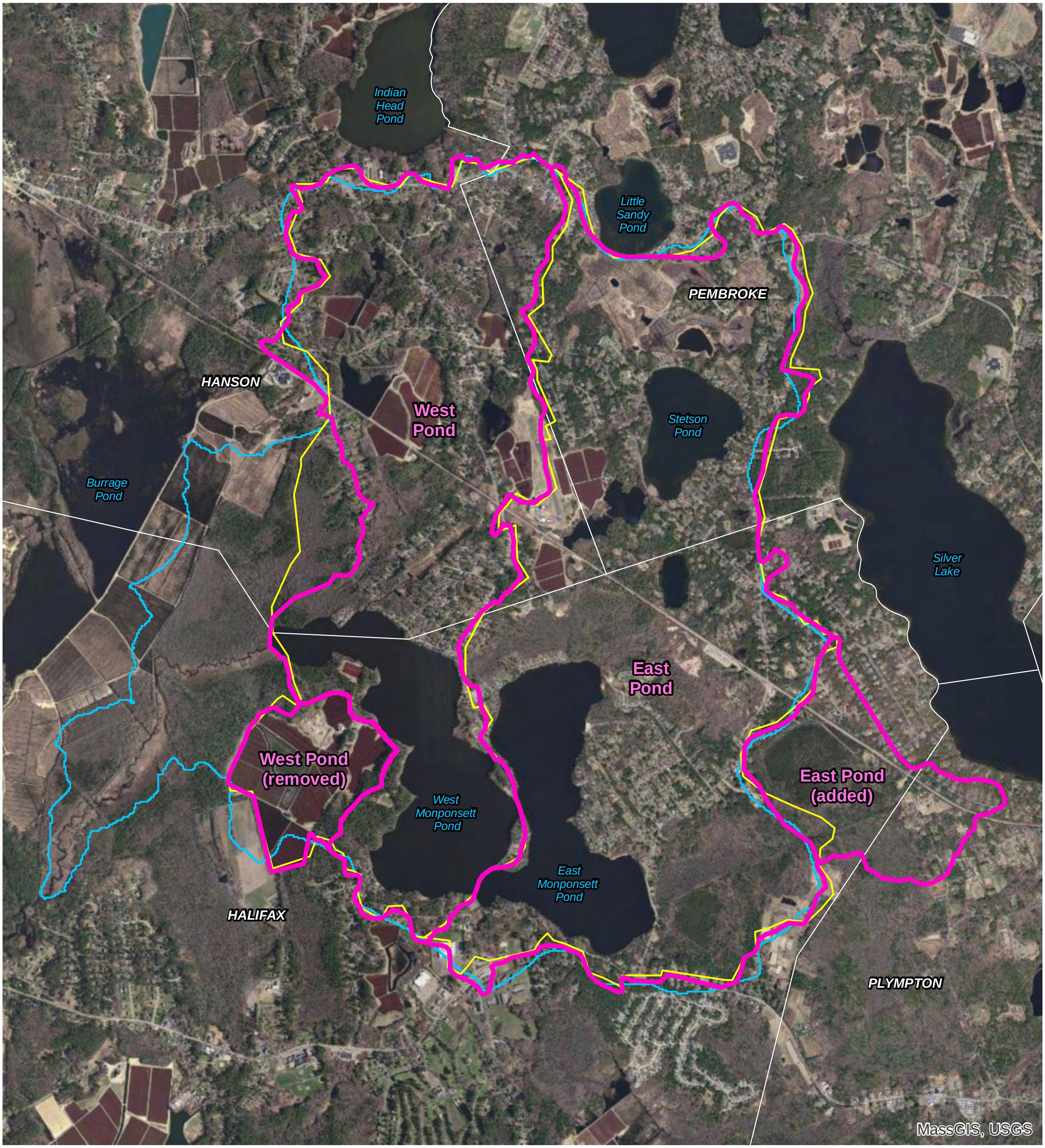
4.1.2 Watershed Delineation

The delineation of watersheds for the Monponsett Ponds used the following sources of information: “hydro” sub-basins used by the SWMI (Brandt and Steeves, 2009), StreamStats (2009) watersheds, a previous Monponsett Pond study (Princeton Hydro, 2013), and two-foot contours and flow lines derived from recent LiDAR elevation data for the Northeast (MassGIS, 2011).

The initial delineation of new watershed boundaries used Geographic Information Systems (GIS) to create LiDAR-based contours and flow lines. These boundaries were then compared with the SWMI and Princeton watersheds. All the watersheds are shown in Figure 8.

Although most of the watershed boundaries were similar among the methods, two areas of discrepancy arose. The area to the southeast of the East Pond was excluded in the SWMI, StreamsStats, and Princeton watersheds, but we decided to include it because our LiDAR tools showed that it flows west to the East Pond. Additionally, the inclusion of this mainly wetland area helped calibrate the water quality model to the observed water quality data from East Pond.

The cranberry farm to the southwest of the West Pond was included in the Princeton Hydro watershed but we decided to exclude it because our LiDAR tools showed that that farms drains west towards Stump Brook (below the pond but above the Stump Brook Dam) and does not enter West Pond directly. In addition, UMass Cranberry Experiment Station (Kennedy, 2015) indicated that only about 0.8 hectare (2 acres) on the north side of the farm drains to West Pond. This decision is worthy of further consideration because the groundwater modeling discussed above for this study, and the observed flat hydraulic gradient between the pond and the dam,



Path: H:\Projects\2015\15000 Stump Brook Flow Restoration\GIS\Maps\Figure6_WatershedDelineation_15000.mxd

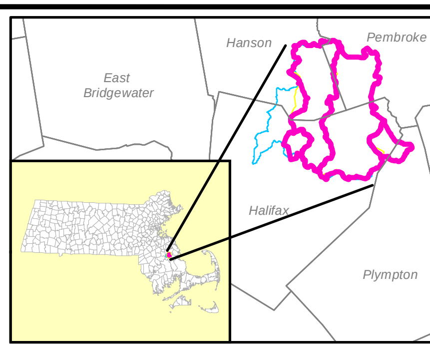
Legend

- Watersheds used for this Study
- Princeton (2013) Watersheds
- USGS (2009) Hydro Unit
- Town Boundaries

N

0 3,000

1" = 3,000 Feet



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Watershed Delineation for Monponsett Ponds

Date: 7/14/2015

Figure 8

indicates the potential for water to occasionally backflow from the portion of Stump Brook above the dam into the pond when Brockton makes large diversions from East Pond.

4.1.3 Pond Water Quality

All available sources of data were pooled to obtain nutrient data on both the West and East Ponds. The primary nutrient parameters of interest to support the modeling work are total phosphorus (TP), total nitrogen (TN), and chlorophyll-*a* (chl-*a*). The sources of information were the following: Department of Health (DPH) beach monitoring program (2009-2010), Lycot Environmental (2014), Department of Environmental Protection (DEP) TMDL Lakes Survey (2001), and DEP Lake Baseline monitoring program (2011-2012).

A summary of the pond water quality statistics is given in Table 10.

Table 10. Pond Water Quality Statistics

Site	Parameter	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)	Chlorophyll-*a* (mg/m^3)
West Pond	Minimum	0.03	0.65	0.6
	Average	0.08	1.49	172.4
	Maximum	0.74	20.10	2000.0
East Pond	Minimum	0.02	0.49	3.9
	Average	0.03	0.67	14.0
	Maximum	0.04	0.98	28.4

4.2 Description of LLRM Model

The Lake Loading Response Model (LLRM) was developed by AECOM (2009) and has been use to model the pond water quality response to watershed nutrient loads. The LLRM is a spreadsheet model with readily-accessible inputs and results. The LLRM is an annual model of flow and nutrient loads that estimates the average annual inflow concentrations, then uses those values and pond characteristics to predict the in-pond concentrations of phosphorus, nitrogen, chlorphyll-*a*, and Sechii disk transparency.

The LLRM takes into account flow and nutrient loading of phosphorus and nitrogen inputs from many contributing sources, including: land use loads, waterfowl, septic systems, point sources atmospheric deposition, and internal loads. A calibrated LLRM model can be used to evaluate alternative pond management scenarios in response to flow or nutrient load changes.

Because the Monponsett Ponds are heavily influenced by Brockton diversions from East Pond, the model was modified to allow point sources (diversions, transfers between the lakes, and augmented groundwater inflow) to and from the pond instead of the watershed (the usual approach). This modification allows the flow and loads to directly affect the pond in an unattenuated manner. Additionally, a model error was corrected to account for the loss of water via evaporation in the computation of net water input to the pond surface.

The LLRM uses metric units so these will be given in this report, with some appropriate conversions.

4.3 LLRM Model Inputs

4.3.1 Precipitation and Flow

Annual precipitation and precipitation coefficients determine the flow of water from the watershed to the pond. The average annual precipitation from the Brockton gauge (USC00190860) for the period 1996-2014 was 52.8 inches per year. Precipitation coefficients for each land use were selected to give a watershed yield of 0.635 meters per year (1.84 cubic feet per second, 25 inches per year), which is the typical average streamflow in Eastern Massachusetts. Precipitation coefficients were selected based on information from Zarriello and Reis (2000), CRWA (2011), and best professional judgment (see Table 12).

Although the model allows the total flow and loads to be split into storm and base flow components, we chose to use just the total flow and loads, since there are no separate attenuation factors in the model.

4.3.2 Land Use and Nutrients

The land use in each watershed was determined using available GIS information (MassGIS, 2005). To simplify the modeling process, original land uses were grouped into functional equivalent groups based on their hydrology and expected nutrient loading. The simplification of original land use to land use group is given in Table 11.

Table 11. Land Use Simplification

MassGIS 2005 Description	Land Use Group
Brushland / Successional	Natural
Commercial	High Development
Cranberry Bog	High Agriculture
Forest	Natural
Forested Wetland	Water
High Density Residential	Medium Development
Industrial	High Development
Low Density Residential	Low Development
Medium Density Residential	Medium Development
Multi-Family Residential	Medium Development
Non-Forested Wetland	Natural
Nursery	Low Agriculture
Open Land	Open
Participation Recreation	Medium Development
Pasture	Low Agriculture
Transitional	Low Development
Transportation	Medium Development
Urban Public/Institutional	Medium Development
Very Low Density Residential	Low Development
Water	Water

Using the land use groups, the land use group areas were determined and nutrient export coefficients assigned from a number of sources (Reckhow et al., 1980; Howes and Teal 1995; DeMoranville and Howes, 2005; Howes et al., 2006; CRWA, 2011; Princeton Hydro, 2013, and Kennedy, 2015). A summary of the final nutrient export coefficients by land use group is given in Table 12.

Table 12. Water and Nutrient Load Coefficients by Land Use

Land use	West Pond Land Area (ha)	East Pond Land Area (ha)	Flow Coefficient (% precip.)	TP (kg/ha/yr)	TN (kg/ha/yr)
Water	65.94	215.58	0.38	0.0	0.0
Natural	174.84	316.61	0.47	0.1	0.5
Open	0.00	5.49	0.53	0.3	2.0
Low Intensity Dev.	110.30	166.16	0.53	0.4	4.0
Medium Intensity Dev.	72.25	113.55	0.62	0.8	8.0
High Intensity Dev.	10.23	12.28	0.72	1.2	12.0
Low Intensity Agric.	0.21	11.30	0.56	1.0	8.0
Medium Intensity Agric.	0.00	0.00	0.53	2.0	12.0
High Intensity Agric.	53.03	68.08	0.49	4.0	24.0
Pond/Atmos. Deposition	124.98	110.03	0.38	0.4	10.0

4.3.3 Septic System Nutrients

Septic systems can contribute both phosphorus and nitrogen to the watershed nutrient loads. Because phosphorus moves poorly through soils, we visually counted only those residences within 100 feet of the pond edge. For nitrogen, all households in each watershed were counted using the 2010 Census Data (MassGIS, 2010). The septic systems numbers are given in Table 13.

Table 13. Septic System Numbers

Septic	Item	West Pond	East Pond
100-ft Buffer	Population	166	215
	Houses	64	87
	Pop / House	2.60	2.47
Watershed	Population	2,309	3,421
	Houses	888	1,383
	Pop / House	2.60	2.47

For septic system loads, a wastewater load of 0.21 m^3/day (55.25 gppd) was used with effluent concentrations of 7.0 and 26.25 mg/L for phosphorus and nitrogen respectively (Metcalfe and Eddy, 2004; Howes et al., 2006).

4.3.4 Water and Nutrient Transfers

The Brockton diversion from East Pond for water supply withdraws an average of about 8.45 Mm3/yr (6.1 MGD). This withdrawal is large enough that it pulls water from both ponds and results in a transfer about 2.80 Mm3/yr (2.00 MGD) of water from West Pond to East Pond. This transfer represents mixture of poor quality water (TP= 0.084 mg/L, TN=1.495 mg/L) from West Pond and from relatively clean groundwater (TP=0.001 mg/L; TN = 0.5 mg/L). LLRM model calibration indicates that the total transfer may be split between West Pond surface water and groundwater. It is likely this additional groundwater is pulled from outside the delineated surface water watershed.

4.3.5 Internal Nutrients

Internal nutrient loads result from the historic cycling of nutrients from the water column into algae and subsequent settling of dead algae on the pond bottom. The nutrients become bound to the pond sediments and are released the following growing season. Under aerobic conditions the release rates are generally low but under anaerobic conditions that last more than a week, as in when the pond becomes stratified, they can become significant.

Since no measurement of sediment release rates has yet been made on the Monponsett Ponds, we estimated the internal nutrient loads. Because the East Pond has good water quality, we assigned zero internal loads to that pond. For West Pond, we estimated the internal loads via the calibration process.

4.3.6 Waterfowl Nutrients

Nutrient loads from waterfowl were not considered for this model at this stage.

4.4 LLRM Model Calibration

The calibration process involves comparing the predicted pond nutrient concentrations from the LLRM model with observed values for both ponds (see Table 10), then making reasonable changes in model parameters. To account for the fact that observed water quality is relatively poor in West Pond in comparison to East Pond, the final model calibration involved adjusting the following parameters: groundwater inflow to East Pond, internal loads to West Pond, and the watershed attenuation factors for both East and West Pond. Calibrated attenuation factors for West Pond were 0.7 and 0.8 for phosphorus and nitrogen respectively, while for East Pond they were 0.25 and 0.32, respectively.

The model calibration focused on the total phosphorus and total nitrogen concentrations since these water quality data were available in sufficient number. Chlorophyll-*a* is predicted by the model but was not used for model calibration because insufficient data were available.

Final calibration errors for phosphorus and nitrogen concentrations for both ponds were less than 10%. The total load and relative contributions of nutrient sources to each pond are given in Table 14. Total flow including groundwater and surface water out of West and East Ponds is 7.1 and 1.2 cfs, respectively.

Table 14. Calibration Nutrient Loads

Nutrient Sources	West Pond				East Pond			
	TP (kg/yr)	TP (%)	TN (kg/yr)	TN (%)	TP (kg/yr)	TP (%)	TN (kg/yr)	TN (%)
Atmospheric	50	9.2%	1,250	16.5%	44	23.8%	1,100	36.5%
Internal	381	70.2%	4,738	62.5%	0	0.0%	0	0.0%
Transfers	-235	-43.3%	-4,179	-55.2%	-7	-4.0%	-1,227	-40.7%
Waterfowl	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Septic System	53	9.8%	3,239	42.7%	28	15.3%	2,057	68.2%
Watershed Land Use	293	54.1%	2,530	33.4%	120	64.9%	1,084	36.0%
TOTAL LOAD	542	100.0%	7,577	100.0%	185	100.0%	3,014	100.0%

4.5 Modeled LLRM Scenarios

A description of the LLRM modeled scenarios is given below:

1. Calibration Scenario. Represents the current condition as best represented by the calibration model. All parameters remain as calibrated.
2. No Diversion Scenario. Represents the extreme situation of eliminating diversions for Brockton water supply. The diversion flow, transfer flow from West Pond to East Pond, and the additional groundwater flow into East Pond are all set to zero.
3. No Internal Load Scenario. Represent a comprehensive treatment of the sediment in West Pond with an alum treatment or the complete removal of sediment from West Pond using dredging.
4. Increased Stump Brook Dam Outflow Scenario. Represents maximizing flow through the Stump Brook Dam (SBD) outlet by leaving the low-level sluice gate wide open. This scenario is conceptualized to result in an approximately two-foot decrease of average annual pond level based on the calculations conducted for this study. As discussed in Section 3.3, that two-foot decline in pond level is likely an overestimate, at least over relatively short time periods of increased dam outflow.
5. Land Load Reduction Scenario. Represents the implementation of structural and non-structural Best Management Practices to reduce overall nutrient loads from developed land uses (residential, commercial/industrial, agriculture, and open) by 50%

A summary of the scenario results is given in Table 15. For comparison, the lake nutrient criteria data for sub-region 84 are also given (EPA, 2001). These numbers correspond to oligotrophic and mildly impaired lakes but exclude mesotrophic, eutrophic and hypereutrophic lakes (Brewster, 2009).

The No Diversion Scenario decreases the simulated TP and TN concentrations in both ponds while also increasing the net outflow from both ponds (Table 15). Net outflow in the LLRM is the residual flow out of the ponds which can be conceptualized as groundwater plus streamflow. Nutrient concentration reductions under the No Diversion Scenario are primarily the result of dilution from a greater volume of water in the ponds.

The No Internal Load Scenario only decreases the simulated TP and TN concentrations in the West Pond since that was the only pond that was modeled to have any internal load to begin with. Treatments to reduce internal loading are effective for relatively short periods of time unless the external loads are also reduced significantly.

The Increased Stump Brook Dam Outflow scenario decreased the simulated TP and TN concentrations in both ponds while also slightly increasing the net outflow from both ponds. Nutrient reductions under the Increased Stump Brook Dam Outflow Scenario occur primarily from increased inputs of relatively clean groundwater in response to the lowered pond elevation.

The Land Load Reduction Scenario resulted in large reductions in nutrient concentrations in East Pond and these values approach or fall below the EPA nutrient criteria. Lesser reductions in West Pond occurred for this scenario because land loads in that pond are a smaller proportion of the total flow because of the high internal loads.

As modeled, a combination of land load reductions, internal load reduction in West Pond, reduced diversions from the ponds, and increased flow through the Stump Brook Dam could potentially bring both ponds at least close too, relevant EPA water quality criteria , although West Pond might still require some additional measures or slightly more stringent load reductions.

Table 15. Scenario Results

Scenario	West Pond		East Pond	
	TP (mg/L)	**TN (mg/L)**	**TP (mg/L)**	**TN (mg/L)**
Sub-region 59 Nutrient Criteria for Oligotrophic and Mildly Impaired Lakes	0.008	0.320	0.008	0.320
Calibration	0.084	1.487	0.029	0.686
No Diversion	0.057	1.092	0.019	0.571
No Internal Load	0.037	0.849	0.029	0.686
Fully Open Stump Brook Dam Low-Flow Sluice Gate and Fish Ladder	0.073	1.357	0.021	0.509
50% Reduction in Land Loads	0.064	1.280	0.004	0.324

4.6 LLRM Model Limitations

The LLRM model is a mass balance model that balances various inputs and outputs to predict water quality conditions in the receiving water. The model used the best available data for inputs and outputs and was calibrated against available pond water quality data. However, as is frequently the case, more data would always be better. The model could have been calibrated against available data using different combinations of inputs and outputs than those simulated here. For example, these model simulations include no loading from the adjacent cranberry bogs but do include significant loading from internal recycling of nutrients from West Pond sediments. This decision was made because observed improvements of pond water quality following an alum treatment indicated significant internal loading as a nutrient source, and because of information obtained from the UMass Cranberry Experiment Station that indicated minimal bog drainage into West Pond. It is entirely possible that reality includes a more significant load from the cranberry bogs and a lesser load from internal loading. Despite the potential inaccuracies inherit in any particular components of the LLRM model, it is considered a useful tool for evaluating the relative effects of various strategies for water quality improvement.

5.0 Summary

The groundwater modeling, spreadsheet calculations of Stump brook Dam flow, and water quality modeling conducted during this study were informative as to the behavior of the Monponsett Ponds hydrologic system under various potential management scenarios. The following are some of the key findings:

- Reducing the diversions from the pond through the as-needed scenario, and particularly the no diversions scenario, should significantly increase the amount of water available in the pond hydrologic system to support increased Stump Brook flow.
- Operation of the low-flow sluice gate has ability to increase flows in Stump Brook and move water out of ponds. Because a wide open sluice gate is simulated to quickly draw down the pond level, particularly if undertaken at the same time as significant diversions are ongoing, the most prudent course of action would likely be to experiment with opening the sluice gate in small increments for limited time periods and observing the impacts on pond stage and stream flow. While only fully open and half open sluice gate positions were evaluated in this study, it is our understanding that the gate is fully adjustable over smaller increments. Incremental, monitored dam management, conducted in concert with a known diversion schedule, should be effective at evaluating optimum settings to enhance stream flow without unduly reducing pond levels.
- Water quality modeling indicates that an aggressive suite of land use load alterations, dam management, and diversion management scenarios would likely be required to create significant improvements in pond water quality. East Pond appears closer to attaining water quality goals than does West Pond and land use load reductions would make the greatest contribution towards East Pond achieving those goals. As modeled, West Pond appears likely to require significant reductions in internal loading and/or loading from adjacent cranberry bogs above and beyond the reductions discussed fro East Pond in order to get closer to water quality goals.

6.0 References

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