SUSTAINABLE WATER MANAGEMENT INITIATIVE REPORT

Monponsett Pond and Silver Lake Water Use Operations and Improvement

SWMI Project No. BRP 2012-06

Prepared for:

Town of Halifax, Massachusetts
Attn: Cathy Drinan, Board of Health
Cdrinan@town.halifax.ma.us

And

Massachusetts Department of Environmental Protection
Jen D'Urso
Jen.Durso@massmail.state.ma.us

Prepared by:

Princeton Hydro, LLC

1108 Old York Road, Suite 1
P.O. Box 720
Ringoes, New Jersey 08551
(P) 908.237.5660
(F) 908.237.5666
www.princetonhydro.com

James Shallenberger, P.G.
JShallenberger@PrincetonHydro.com

Paul Cooper
PCooper@PrincetonHydro.com

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In December 2012, the Town of Halifax applied to the Massachusetts Department of Environmental Protection (MADEP) for a grant pursuant to the Sustainable Watershed Management Initiative (SWMI) program. In March 2013, MADEP announced that Halifax was awarded funding to hire a consultant to evaluate water management practices and recommend options to improve water quality and provide sustainable flows in Stump Brook. This document is a comprehensive report of the activities, findings, and recommendations prepared by Princeton Hydro, LLC of Ringoes, New Jersey pursuant to SWMI project "BRP 2012-06 – Monponsett Pond[1] and Silver Lake Water Use Operations and Improvements".

The City of Brockton's water supply (BWS) system relies on water sourced from Silver Lake for more than 90% of the finished water the City delivers to its roughly 110,000 customers. Silver Lake is located approximately 20 miles outside of Brockton in Kingston, Massachusetts. Brockton's withdrawal from Silver Lake is part of a more than 100-year old, complex water management operation that now diverts surface water across two drainage divides into a third for treatment, then delivery and ultimate consumption in a distant part of one of the contributing watersheds.

The BWS system is controversial, contentious, and various perspectives flourish. The most prominent stakeholder issues include:

- Maintain cost and reliability of source water for the City of Brockton
- Reduce negative impacts of cultural eutrophication in Monponsett Pond, Furnace Pond, and Silver Lake
- Improve hydrologic connectivity and re-naturalize flow regimes to Herring Brook, Stump Brook, and Jones River to support aquatic life
- Alleviate flooding effects on lakeside and riverfront properties.

This report is organized into five main sections, each with several subsections. The first main section begins with a timeline of key infrastructure, legislative, and water use trend developments that provide context to the findings and recommendations in this report. Section 1 also includes a description of the objectives that underpin the Sustainable Water Management program including stream flow criteria; a discussion of ways to consider the value of clean water; and, a comparison of the terms *sustained* and *sustainable*. The project setting is characterized in Section 2 with subsections separated into hydrogeologic traits; compilation of daily climate records observed since 1900; and basic aspects of the water system infrastructure and operation. In Section 3 we assess a water balance in detail for Silver Lake, Monponsett Pond, and Furnace Pond using monthly statistics derived from daily flow and climate data for the period 1997 – 2012. Section 4 includes nutrient loading analyses and Section 5 presents trophic structure modeling pertinent to the cultural eutrophication of each lake in the system. In Section 6, we provide a summary of the overall findings and emphasize disparities between current practice and sustainability. We provide conceptual management alternatives in Section 7. Section 8 contains references cited. Figures, tables, and certain calculations are embedded in the narrative.

[1] As referenced herein, "Monponsett Pond" refers to two basins, East Monponsett Pond and West Monponsett Pond, that share a common water surface elevation and are connected by culvert.

1.0 BACKGROUND

Following the American Civil War, southeast Massachusetts, led by Brockton, became the epicenter of US shoe-making, textile, and related industries. As the 19th century closed, Brockton's demand exceeded its local ability to supply water from the Avon Reservoir (a.k.a. Brockton Reservoir) and in 1899 the Massachusetts Legislature enacted Chapter 356; "*An act to authorize the city of Brockton to take an additional water supply*."

1.1 Acts of the Massachusetts Legislature with Respect to Brockton's Water Supply

Chapter 356 Section 1 reads as follows: "The city of Brockton, for the purpose of increasing its water supply, may take and hold the water of Silver Lake in the towns of Plympton, Kingston, Halifax, and Pembroke, and may also take, by purchase, or otherwise, and hold all lands, rights of way, and easements necessary for holding **and preserving such water and protecting its purity**; *provided*, that **water for domestic purposes, and lands necessary for preserving the quality of such water, <u>shall be taken only with the advice and approval</u> of the state Board of Health**." [Emphasis added[2].]

At its outset, Act 356 authorized the diversion of water across the natural watershed divide; from the headwaters of the Jones River watershed into the Taunton River watershed. And although Act 356 pre-dated the current framework of state and federal statutes enacted to manage and protect environmental resources, the Legislature in 1899 exercised considerable foresight regarding such matters by stipulating conditions to preserve and protect water quality and by conferring oversight to the state Board of Health.

In response to severe drought conditions in the early 1960s, in 1964 the Massachusetts Legislature approved Act 371; "*An act establishing the Central Plymouth County Water District and authorizing the City of Brockton to extend its source of water supply.*" The legislators declared Act 371 to be, "… **an emergency law, necessary for the immediate preservation of public convenience.**" [Emphasis added.]

In addition to establishing the Central Plymouth County Water District[3], Act 371 authorized Brockton to divert water to Silver Lake from sources located in two different watersheds. Act 371 authorized flow from the Taunton River watershed by diversion of Monponsett Pond into Silver Lake and from the North River basin, by diversion of Furnace Pond into Silver Lake. Act 371 set timing and water elevation conditions on when diversions into Silver Lake could occur; the water elevation conditions triggered Brockton to establish or modify water control structures at Monponsett and Furnace Pond, respectively.

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[2] Princeton Hydro does not assert claims regarding legal status of items herein; rather, our purpose is to illustrate context.

[3] The Central Plymouth County Water District (CPCWD) was established by the Act to consist of an Advisory Board and a Commission with duties to provide oversight for water supply resources in the affected communities. The CPCWD has largely been inactive since it was created.

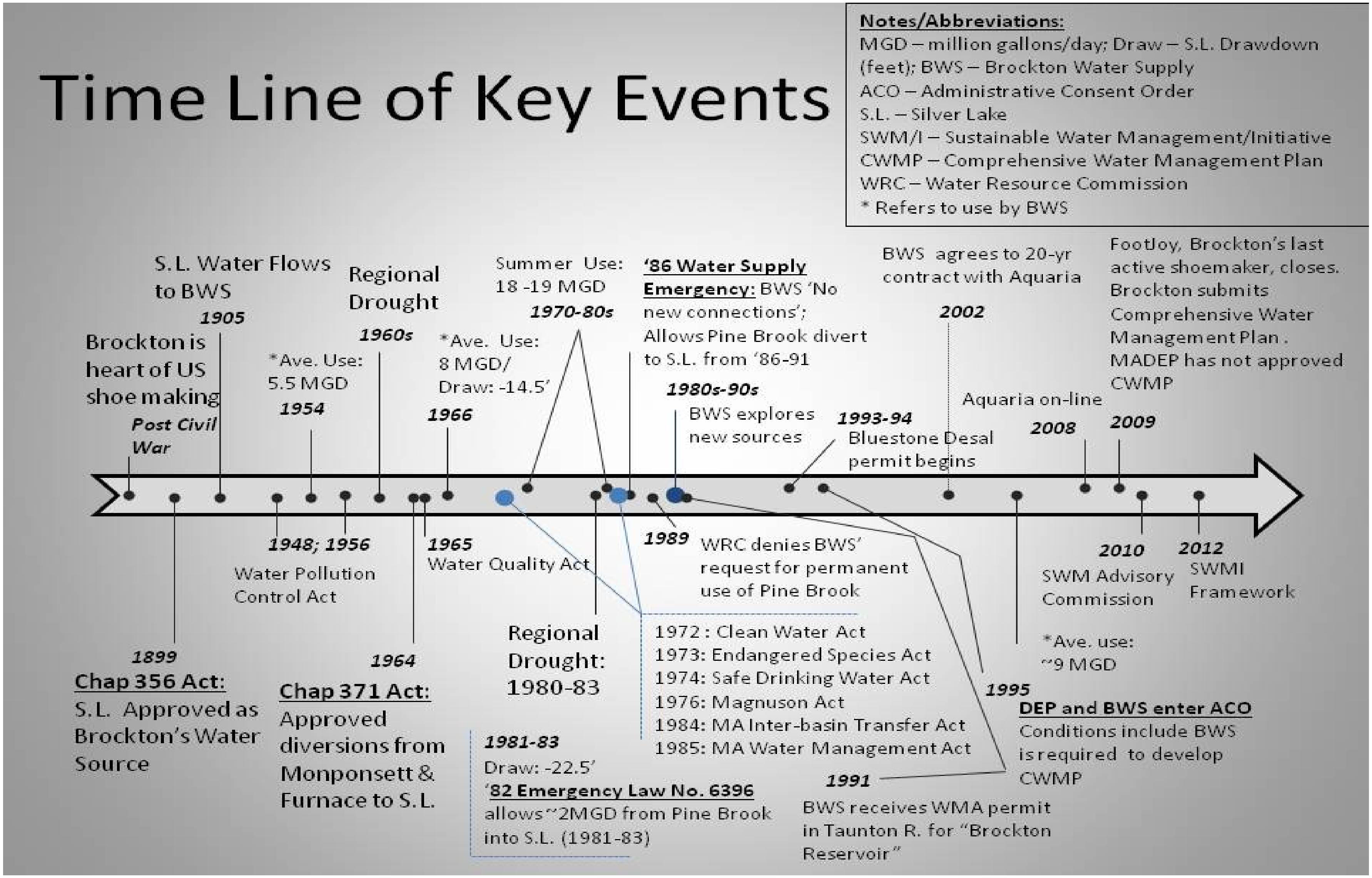


FIGURE 1. Time line (not to scale) of key events involving Brockton's water supply system as well as major federal and state legislative actions pertinent to natural resources management.

The Act also required Brockton to construct a water treatment plant at Silver Lake with through-put treatment capacity of "not less than" 20 MGD.

Of note, Section 8 of Act 371 proclaimed, "*… nothing in this act shall be construed as preventing the normal use of the aforesaid Furnace Pond and Monponsett Pond for bathing, boating, fishing and other purposes, …*". And continuing, Section 8 also stated, "*There shall be no diversion of water from Furnace Pond or Monponsett Pond into Silver Lake, if, in the opinion of the department of public health, the diversion of such waters would endanger the public health.*

Chapter 237 of the Acts of 1981 ("*An act further regulating the source of water supply for the City of Brockton*"), required establishment of water control structures to prevent diversion of water from Monponsett Pond below elevation 52 feet and to prevent diversion of water from Furnace Pond below elevation 56 feet (National Geodetic Vertical Datum 1929).

As a consequence of its expanded customer base (Brockton experienced an increase in residential development and population between 1960s-1980s) and deteriorating, leaky water conveyance system, average daily water use grew from approximately 5.5 million gallons per day (MGD) to more than 13 MGD between the mid-1950s and early 1980s and average summer season use peaked at 18-19 MGD by the late 1970s – early 1980s.

In 1981, during a period of intense drought (1980-'83), the Silver Lake water surface was drawn down more than 22 feet below the lake's outlet elevation and was even lower than the BWS intake level. In 1982, an emergency law (no. 6396) was enacted that authorized diversions from Pine Brook into Silver Lake that averaged approximately 2 MGD between 1981 and early 1983.

FIGURE 2. Photograph from 1981 showing emergency diversion of approximately 2 MGD from Pine Brook into Silver Lake during episode of severe drought and drawdown. Pine Brook emergency diversions lasted 1981-'83.

Through the mid-1980s, the BWS system was in crisis. In 1986, the Massachusetts Department of Environmental Protection (MADEP) issued Brockton with an Administrative Order (AO) followed by an Emergency Declaration; the latter required Brockton to control its water demand and develop two local water supplies (i.e., Hubbard Avenue well and Brockton (a.k.a. Avon) Reservoir). The Emergency Declaration also allowed BWS to divert water from Pine Brook into Silver Lake for six months per year between 1986 and 1991. In 1988, BWS applied to the Water Resource Commission (WRC) seeking permanent use of the Pine Brook diversion; however, the WRC denied BWS' request and an appeal by BWS to State Superior Court upheld the WRC's decision; meaning that BWS was not authorized permanent use of Pine Brook to supplement Silver Lake.

In 1995, Brockton and the Massachusetts Commonwealth entered into an Administrative Consent Order (ACO; ACO-SE-95-5005[4]) that discharged the Emergency Declaration and required BWS to establish a Board of Water Commissioners; appoint a full-time professional water systems manager; undertake a series of specific actions intended to coordinate water supply activities with certain other communities; develop a Comprehensive Water Management Plan (CWMP) for existing supplies; and assess the possibility of developing new water supply wells for Brockton. The intent of the CWMP was to address many of the same stakeholder concerns identified in this report. Among the MADEP's core requirements for the CWMP was a provision that Brockton optimize its water supplies in manners that minimize environmental impacts.

By 2009, Brockton had met certain of the ACO requirements. Of note, although Brockton had submitted several versions of its CWMP, including responses to MADEP review comments, as of 2013, the Department had not approved the CWMP, the ACO remained in effect, and BWS had not developed a strategy to reduce environmental impacts.

1.2 Alternative Water Supply Sources – Focus on Desalination

The 1986 Emergency Declaration as well as the 1995 ACO, in part, required BWS to seek water sources that could off-set reliance on the Silver Lake supply system. In the late 1980s, BWS unsuccessfully tried to permanently integrate Pine Brook into its Silver Lake supply network. In 1991, BWS obtained a Water Management Act (WMA) permit to re-activate the Avon/Brockton Reservoir as a water source. Avon Reservoir dates from the 1880s and had been used by BWS until the 1950s. The original safe yield of Avon Reservoir was 1.5 MGD (Kasperson 1969); however, the 1991 WMA permit limited use to 0.83 MGD.

In the 1990s, Brockton explored the possible development of groundwater supply wells in the City, but low yield and/or poor water quality were cited as reasons why local groundwater sources have not emerged as significant contributors to the BWS water supply mix.

In the mid-1990s, Brockton also evaluated the use of Taunton River as a source of water, yet that proposal was rejected due to opposition that considered the project environmentally unsound. The Brockton Water Commission also considered linking to the Massachusetts Water Resources Authority

[4] ACO-SE-1995-5005 was subsequently amended several times.

(MWRA), a system that delivers water to the Boston Metropolitan area from a reservoir network located in central and western Massachusetts. The Commission dismissed connecting to MWRA because of concerns about rising water costs as well as financing MWRA projects that were not tangible to the City's own economic development plight (Crawford 2013).

Beginning in the early 1990s, a desalination plant began to take shape that offered a viable alternative water source for Brockton. The Dighton desalination plant, first called Bluestone and later renamed Aquaria, was based on an intake feature located in the tidal portion of the Taunton River at Dighton, Massachusetts approximately 16 miles downriver from Brockton. The treatment plant was based primarily on reverse osmosis (RO) technology. The plant's location was selected to maximize RO efficiency by extracting Taunton River water during part of the out-going tide cycle when the raw water bears its lowest average dissolved solids load. The Dighton plant was designed and built with capacity to finish (i.e., treat to potable use standards) 5 MGD at optimal operating conditions, based on a maximum intake rate of approximately 21,000 gallons per minute, which is equivalent to roughly 5.5 MGD based on the average tide cycle "windows" (Jeff Hanson, personal communication 2013). Typically, summer low-flows in the Taunton River reduce RO treatment efficiency because lower freshwater discharge in the non-tidal river reach means higher dissolved solids loads at the Dighton intake. Under normal climate patterns, the months August through October provide less than optimal operating conditions for the Dighton plant simply because the raw water source is too salty. For 10 months each year, the Dighton plant is capable of providing 5 MGD treated water to BWS.

Beside its RO efficiency constraints, which essentially amount to an intake limit coupled with seasonally elevated dissolved solids, the Dighton plant has a secondary limit to its maximum treatment capacity; i.e., the static pressure capacity of the 15-inch distribution pipeline to Brockton.

In 2002, BWS entered into a contract with Aquaria that included payments from BWS to Aquaria for 20 years once the desalination plant became operational. The contract fee structure was coupled to firm commitments by Aquaria that would incrementally increase the supply of Dighton water to BWS beginning with 1.9 MGD in the first year of availability (CDM 2008). Based on the water supply commitment schedule, by 2013, Aquaria must be capable of supplying approximately 3 MGD to BWS.

The Dighton plant became active in 2008 and as of this report date, the Aquaria desalination plant is capable of supplying approximately 3 MGD of treated water to BWS, yet BWS purchases only enough water from Aquaria (~0.3 MGD) to ensure that emergency supplies are ready if needed. In 2009, BWS was projected to provide base payments to Aquaria of approximately $4M pursuant to the contract (CDM 2008). In its response to MADEP review comments regarding the CWMP, BWS stated (CDM 2009), "*DEP must remember that Aquaria was always intended to be, and remains, a supplemental water source*."

1.3 Acts of the Federal and State Legislatures With Respect to Natural Resources Management

Until the late 1800s, resource exploitation and pollutant discharge activities in the U.S. were largely unrestrained. By the early 20th century, the rapidly growing industrialization movement meant that some enterprises successfully asserted dominant common law positions owing to the societal importance/concentrated economic and political power of their particular industry. Other cases struck more subtle common law balances between industry and neighbors (Aspen Law website, 2013).

Some of the earliest Federal legislation initiatives regarding natural resources management emphasized the maintenance of water supply as well as the protection of water quality; i.e., Water Supply and Water Pollution Control Acts of the 1940s, '50s, and '60s. Subsequent legislative actions during the 1970s – '80s focused more specifically on aspects of water quality (as well as solid waste management and air quality), especially addressing pollutant sources and attaining specific numerical measures of water quality. During this period, legislation such as the Endangered Species Act and Magnuson Act also acknowledged ***habitat*** as essential units of natural resource management. More recently, greater understanding of linkages between water supply/water quality and overall watershed ecosystem functions have led to sustainable management initiatives that seek to balance human and ecological uses of natural resources, especially water.

1.4 Natural Flow Regime

The quantity, timing, and quality of water flows is integral to managing water allocation required to sustain ecosystems, human livelihood, and societal well-being. River biota evolved in response to dynamic combinations of magnitude, duration, frequency, timing, and rate of change of flow as well as physicochemical traits of the water through such flow variation (Nilsson and Renöfält 2008). The body of regulatory emphasis regarding flow management to date has concentrated on adhering to a minimum low-flow threshold, rather than maintaining natural variability within the system.

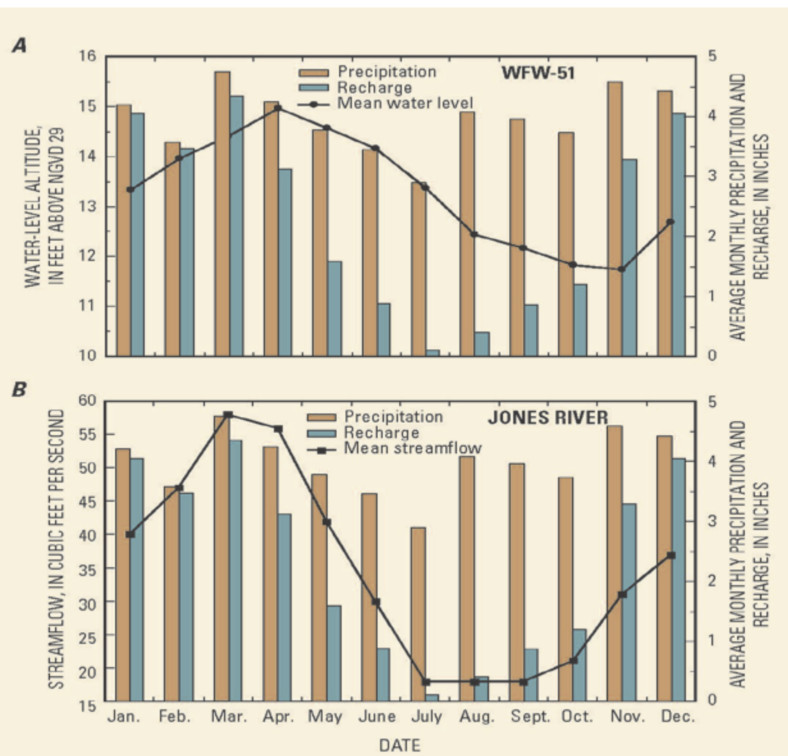


FIGURE 3. Charts of long-term average monthly groundwater elevation (above) and stream flow (below) for parts of southeast Massachusetts. [Source: Masterson and Walter 2009]. Note that while the Jones River hydrograph does exhibit a natural flow pattern at Kingston, MA, actual flows in the Jones River were altered by barriers as well as periods of interrupted/altered outflow from Silver Lake.

Figure 3 illustrates examples of hydrologic variability in groundwater elevation, stream flow, precipitation, and recharge in southeastern Massachusetts. The charts depict long-term monthly average conditions for an observation well in Wareham, MA (Figure 3 above) and a stream gauge on Jones River in Kingston, MA (Figure 3 below). Groundwater level data represent averages over a 45-year span;

stream flows encompass 40 years of observation; and, climate records cover 75 years. The monthly patterns for groundwater level, stream flow, and recharge are all correlated because these factors are inter-related.

As indicated by the long-term average stream flow in Jones River at Kingston, the low flow periods in July/August are inherently vulnerable points for prolonged stress to manifest in the ecosystem.

1.5 What is Sustainable Water Management?

Water occupies at least three critical, yet distinct roles that dovetail in human – environmental interactions (Lant 2004). First, water contributes vitally to human health; whether for potable domestic or for sanitation purposes. Next, water is a raw material necessary as a production factor for industrial and marketable goods, agriculture/livestock, transportation, and energy. Lastly, water is also the primary factor in producing ecosystem services; where *ecosystem services* refers collectively to the items that benefit humans and human society, including clean water, clean air, fisheries stocks, lumber, recreation, etc. The multitude of ecosystem services emanate from the various components of the hydrologic cycle. Although listed above in a specific order, priority rankings for the three critical roles of water identified herein is a matter of perspective and that fact lies at the center of the controversy of Brockton water supply management.

In 2010, Massachusetts established the Sustainable Water Management Initiative (SWMI), an associated Advisory Committee, and a technical subcommittee all combined with an objective to develop and implement water policy that supports ecological needs and fulfills human economic requirements. The overall principle adopted by SWMI is stated as:

> *The Commonwealth's water resources are public resources that require sustainable management practices for the well-being and safety of our citizens, protection of the natural environment, and for economic growth.*

There is a fundamental difference between the terms *sustainable* and *sustainability* that is important to note with respect to water supply. In certain traditional engineering and hydrogeologic contexts, sustainable refers to the withdrawal rate of water that can be maintained over time without dewatering the system, whereas sustainability considers effects to a broad range of conditions including water quality, ecology, and socioeconomic factors that must respond to changes in steady-state status that occur due to withdrawal (Devlin and Sophocleous 2004). The magnitude of long-term water withdrawal that exceeds sustainability depends on the hydrologic effects that society is willing to tolerate, including the actual cost of infrastructure, labor, energy, and related items necessary to obtain, treat, and distribute water.

1.6 Key Components of Sustainable Water Management Initiative Framework

Beginning in 2014, the SWMI framework will guide MADEP's permitting via the Water Management Act. The SWMI framework has three key parts:

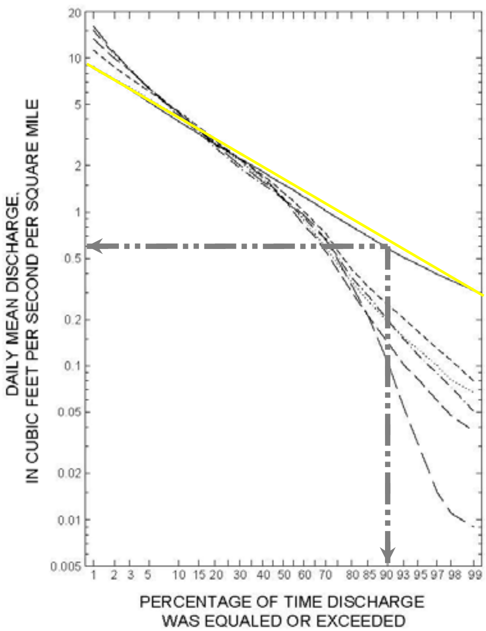
I. **Safe Yield** – the maximum amount of water withdrawal that is allotted at a major basin scale during drought conditions;
II. **Seasonal Streamflow Criteria** – emphasis on maintaining the magnitude and timing of natural flow regime seasonally and at a sub-basin scale based on negative relationships between aquatic health and groundwater withdrawal and impervious surfaces; and,
III. **Baseline** – a basin-scale reference point against which requests to withdraw water will be compared to assess whether a request is an increase for the particular basin.

Safe Yield

At its standard approach, the SWMI Safe Yield amounts to 55% of the annual 90th percentile (Q90) simulated non-impacted[5] flow that was calculated for the main stem river of a particular basin. The annual Q90 is the stream flow that is exceeded 90% of the time throughout a year. The Q90 statistic describes a low flow condition of a river. The annual Q90 flow is combined from model-simulated monthly non-impacted Q90 flows. Simulated non-impacted Q90 conditions are considered by MADEP to generally represent the state's severe drought of 1965 (MADEP 2012). Using stream flow gauges for index watersheds, flow duration curve (FDC; refer to Figure 4 for example of FDC of select New England rivers) statistics are transformed to continuous time-series stream flows for un-gauged watersheds by relating sets of basin characteristics such as proportions of forest/wetland/impervious cover, geology, watershed landform, basin area, stream gradient, etc. (Archfield et al. 2007). In effect, SWMI determined that the volume of water that can be removed 'safely' from a major watershed equals 55% of a statistically conservative estimate of the drought flow for the watershed's largest river. By extension, the remaining 45% of the watershed's estimated annual base flow is available in the river for drought protection and to fulfill the statutory need that withdrawals remain dependable.

The standard Safe Yield estimation approach of SWMI is not applicable to the hydrogeologic conditions of southeastern Massachusetts; i.e., the Plymouth – Carver aquifer system, Cape Cod, Nantucket Island, and Martha's Vineyard (MADEP 2012). Most of Brockton's water source originates in the Plymouth – Carver aquifer system, an area that consists of glacially-derived sand and gravel deposits. Southeastern Massachusetts differs from other parts of the Commonwealth in that much of the groundwater in the aquifer systems discharges directly to the ocean rather than to rivers. Additionally, rivers in the region tend to be shallow and exhibit relatively stable, groundwater-driven flows. Figure 4, illustrates the relative stability of discharge in the Jones River, which is underlain by the Plymouth – Carver aquifer system, as compared to some other New England rivers.

[5] USGS/MADEP models estimate a natural flow condition that is unaffected by water withdrawals, dams, or other flow restrictions.



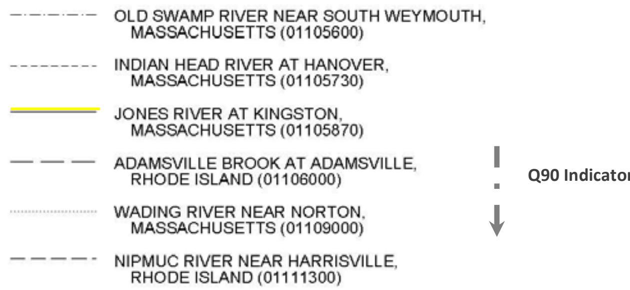


FIGURE 4. Flow Duration Curve (FDC) for select New England rivers including Jones River at Kingston, MA. Note that among rivers depicted, Jones River occupies a distinct hydrogeologic setting. From the FDC, the 90th percentile (Q90) daily stream flow is indicated for Jones River as 0.6 cubic feet per second (cfs). Note that Q90 for Jones River is between 2X and 6X higher than the Q90 for the other rivers in this data set. [Source: Bent 1995].

For the atypical conditions of southeast Massachusetts that includes Silver Lake; i.e., headwaters to Jones River, the Safe Yield estimate was based on 25% of the monthly mean simulated non-impacted flow values for the Jones River as calculated by Archfield et al. 2009. The value 25% of monthly mean estimated non-impacted flows for Jones River was considered to approximate 55% of the monthly Q90 flows for the Jones River basin (MADEP 2012). Based on the preceding approach, the Safe Yield estimate for the Jones River watershed to the river mouth and including Silver Lake, but excluding the across-basin diversions into Silver Lake, is 12.6 MGD (MADEP 2012). Note that the average BWS withdrawal from Silver Lake is approximately 9 MGD or more than 70% of the total Safe Yield estimate for the entire Jones River basin. Furthermore, BWS is not the only public water supplier in the Jones River (or Taunton or North River) basin. The Towns of Kingston, Duxbury, Plympton, and Pembroke collectively withdraw approximately 1.7 MGD from the Jones River basin.

Seasonal Streamflow Criteria

In developing Seasonal Streamflow Criteria, biological categories of flowing waters were established according to existing conditions of the fishery. Fishery condition was expressed as the relative abundance of fluvial fish. A USGS regression model (Armstrong et al, 2011) that incorporates flow, impervious cover, and various natural basin traits was applied to discriminate five distinct biological categories – refer to Figure 5. Category 1 represents high quality habitat with relatively slight human alteration (e.g., in terms of flow manipulation and impervious cover) that exhibits a rich and diverse assemblage of fish; whereas, Category 5 reflects severely altered habitat as expressed by the fish community assemblage. While the regression model has limitations, especially for predictions at the site-specific level, overall, the regression relationship between rate of withdrawal and fluvial fish community is clear (Paul 2012); "*sites with high rates of withdrawal tend to have significantly fewer fluvial fish than sites with lower withdrawals*."

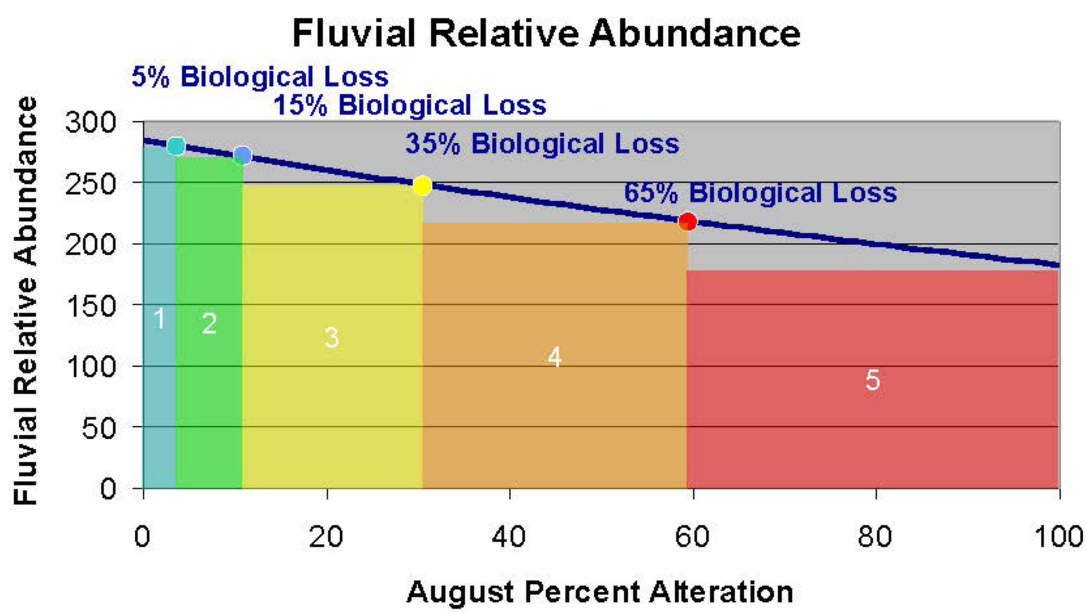


FIGURE 5. Chart of Biological Criteria based on Fluvial Fish Relative Abundance showing categorical alignment with modeled proportions of alteration from the estimated August median (P50) stream flow. Percent alteration from August P50 flow is modeled based on groundwater withdrawal. [Source: Richards 2010].

In watersheds with low impervious cover, Groundwater Withdrawal Levels (GWL), estimates of altered flow in a stream due only to groundwater withdrawal, correspond to the inflection points in the biological categories derived from the estimated August median (P50) flows (MADEP 2012). The Seasonal Streamflow Criteria are the maximum recommended water withdrawals specific to protect each of the habitat categories. In developing Seasonal Streamflow Criteria, alteration of the August P50 flow was considered the appropriate benchmark because in August, typically demand is high and flow is low; therefore, managing withdrawals to balance water availability at such critical timing makes sustainability a primary driver.

Baseline

In the SWMI framework, baseline is the reference point against which new or expanded withdrawal requests are to be compared. For each basin, baseline is the highest of the 2003 – 2005 average water use plus 5%; or, the 2005 water use plus 5%. The additional 5% is a factor that allows for economic growth; however, if baseline equals the registered volume, then no additional water use can be authorized. Additionally, baseline cannot be less than the registered volume; baseline must comply with existing permitted volume; and, baseline cannot exceed the Department's 20-year forecasts (MADEP 2012).

Public water systems (PWS) with sources in multiple basins must adhere to the individual baseline requirements of each basin in the PWS' source mix.

The SWMI framework establishes three tiers for proposed water withdrawals that are based on the combination of whether the proposal is an increase in baseline and whether the proposal is predicted to alter the GWL and/or Biological Category. Proposed water withdrawals that exceed baseline and that are predicted to alter GWL and/or Biological Category are required to develop and implement a mitigation plan regarding the withdrawal in excess of baseline.

2.0 SITE SETTING

The City of Brockton and its water supply sources are located in Plymouth County, in the glacially-influenced Seaboard Lowland section of the New England physiographic province.

The BWS regional landscape appearance is dominated by unconsolidated material that was transported and deposited through Pleistocene glacier contact (e.g., moraines), glacial meltwater (e.g., stratified sand and gravel deposits), and as basin relics of ice block features (e.g., kettle ponds and wetlands). The region is characterized by an abundance of lakes, ponds, peat-filled wetlands, streams, and small rivers intermingled within a gentle undulating landscape (refer to Figure 6).

The BWS system diverts water from headwaters portions of three watersheds as follows: (1) Furnace Pond with natural outlet Herring Brook is located in the North River watershed; (2) Monponsett Pond with natural outlet Stump Brook is located in the Taunton River watershed (same watershed that includes City of Brockton); and, (3) Silver Lake is the headwaters of the Jones River, located in the Jones River watershed.

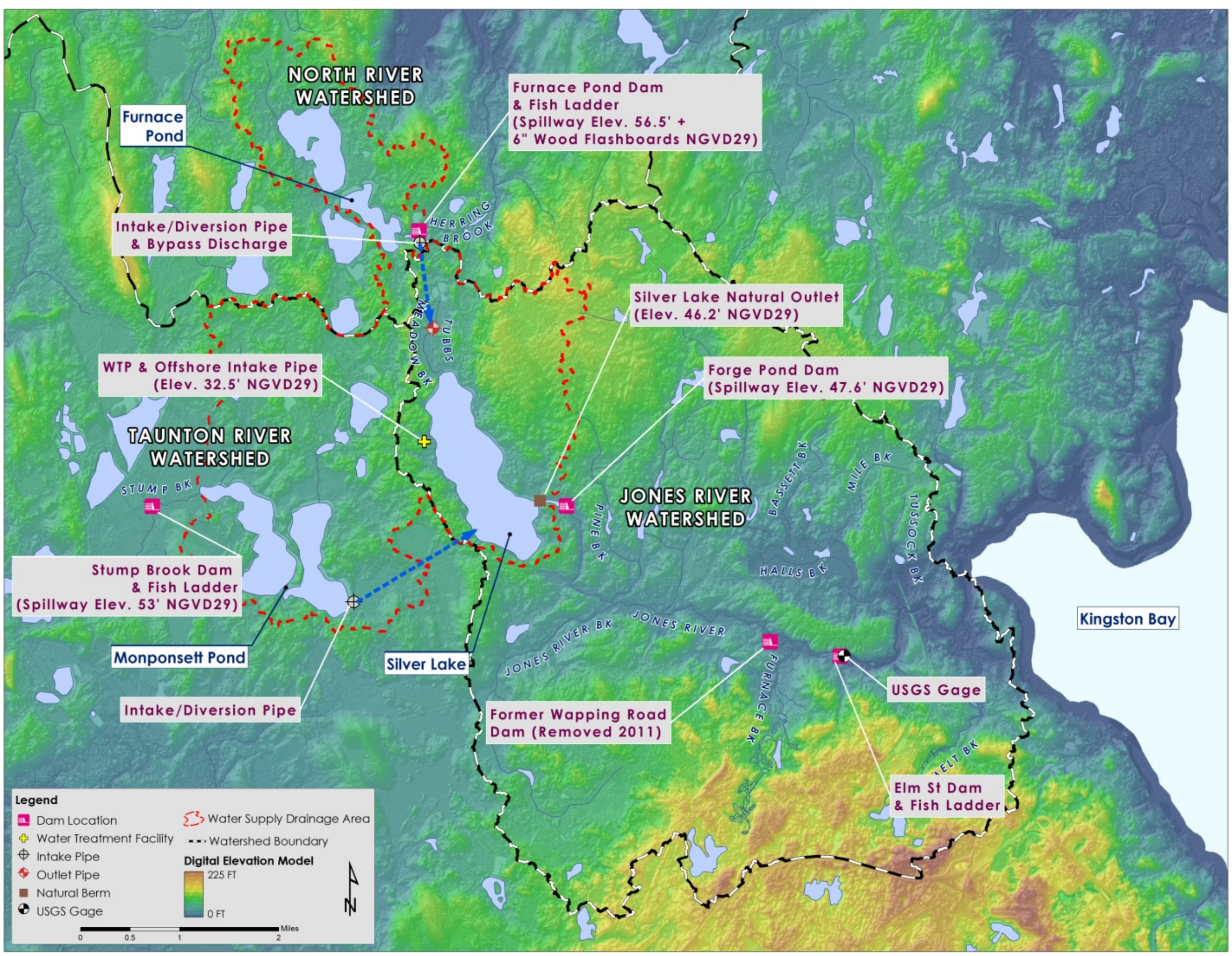


FIGURE 6. Subwatershed boundary map for the primary sources of Brockton's water supply system and individual water supply unit drainage areas.

2.1 Regional Hydrogeologic Traits

The primary water-bearing deposits in the BWS area are stratified sand and gravel of the Plymouth – Carver – Kingston – Duxbury (PCKD) aquifer system (Masterson et al. 2009). The regional, unconfined PCKD aquifer system water table is shallow and frequently intersects the landscape's variable surface, particularly the many relic ice block features (e.g., kettle basins).

Interactions between surface water features, including wetlands, and groundwater largely are determined by the position of local and regional flow paths. Figure 7 conveys the fact that a common, general regional water table is exhibited in the project area. While local elevation differences impart subtle variability, water surface elevations, particularly those within the Brockton water supply setting, adhere to a narrow range. Moreover, based on the hydrogeologic framework of the region, streams and rivers gain groundwater throughout their length.

Proximity to the coast sets a regional base elevation for the water table and also imparts a mixing zone between freshwater that originates inland, and seawater. Additionally, because seawater is denser than freshwater, a freshwater lens overlies saltwater. In some areas, excessive groundwater pumping has contaminated freshwater supplies.

The depth to bedrock surface in the vicinity of BWS features; i.e., Silver Lake, Monponsett Pond, and Furnace Pond, ranges from approximately 20 to 170 feet. The relatively thin, yet highly permeable and transmissive sand and gravel deposits of the PCKD aquifer system are extraordinarily efficient in terms of recharge and movement of groundwater. Masterson et al. (2009) reported hydraulic conductivities in the stratified sand and gravel deposits that range above 150 feet per day. Conversely, crystalline bedrock in the region generally supports wells of poor yield. Note that the City of Brockton is largely underlain by crystalline bedrock and supply wells in the City tend to be of sufficient yield only for on-lot domestic or irrigation demands.

Although a common regional water table is expressed in this landscape, rivers exhibit natural watershed areas that are based on topography. The BWS system artificially consolidates water from three separate river basins (e.g., headwaters portions of Taunton, North, and Jones), then BWS exports an average of 9 to 10 MGD to a distant part of the Taunton River watershed where the water is used and subsequently discharged into the Taunton River. In addition to the treated water volume that is used directly in the BWS distribution system (i.e., 9-10 MGD), during the diversion season (October through May) and in response to certain events outside of the diversion season, BWS diverts water from the Taunton (Monponsett Pond) and North (Furnace Pond) River watersheds into Silver Lake during periods in which water occasionally discharges from Silver Lake into Jones River.

In contrast to an ecological or hydrological perspective, BWS regards the artificially interconnected surface features that include Silver Lake, Monponsett Pond, and Furnace Pond as though they adhere to a single common watershed.

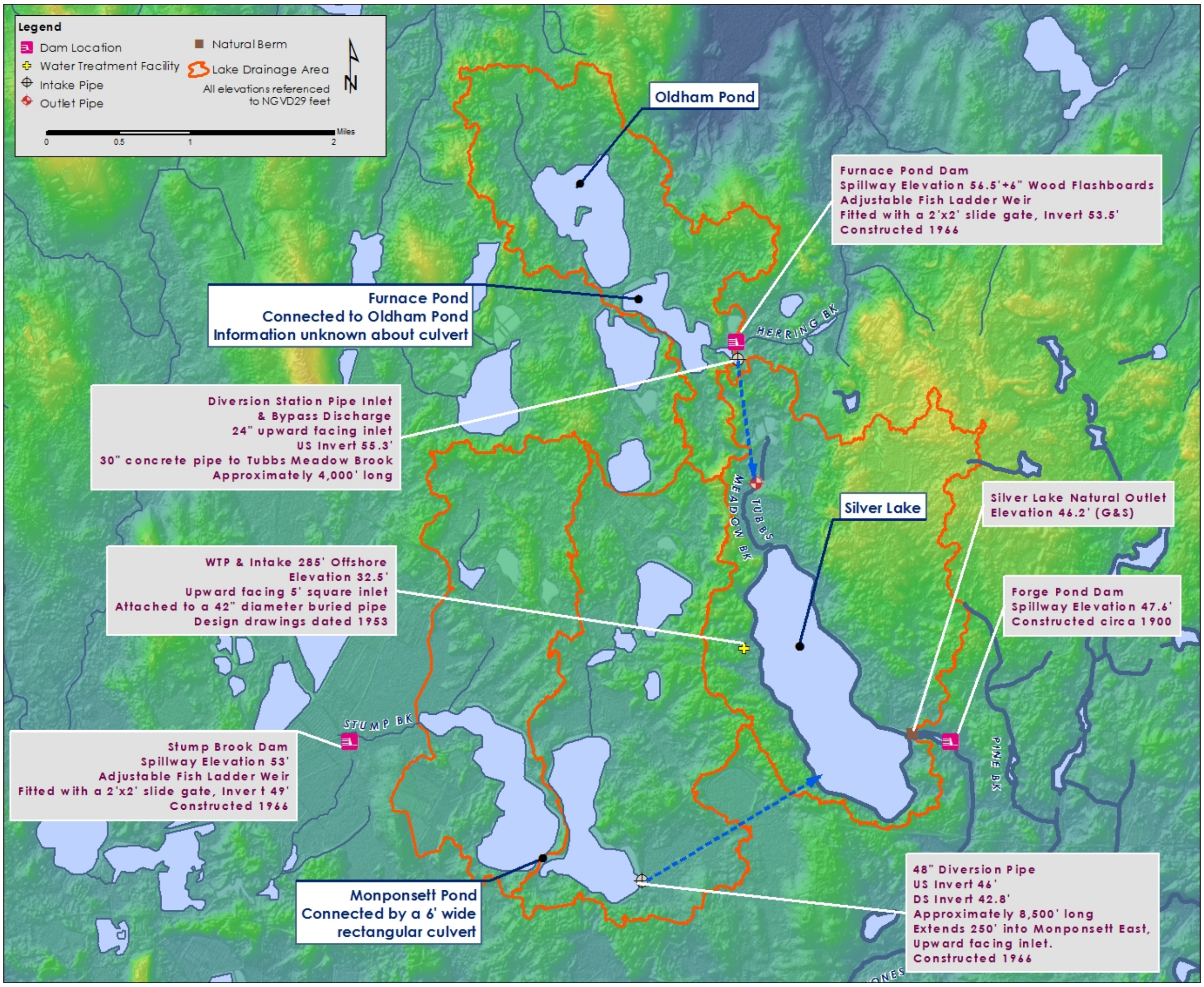


FIGURE 7. Project location map depicting regional topography, surface water features and their individual drainage areas, and major components of Brockton's water supply system.

Several USGS studies reinforce these findings: Masterson and Walter (2009) reported that 57% of annual precipitation infiltrates the land surface and becomes groundwater recharge; Carlson and Lyford (2005) reported comparable groundwater recharge for the region. Both of the referenced USGS reports also stated, due to high recharge capacity, there is minimal runoff for the region. Ultimately, the fate of infiltrated water on a regional basis is well defined; USGS reported ~95% is discharged either as streamflow or as groundwater seepage at the coast, with diversions of surface and groundwater accounting for the balance. True consumptive use of the water from either public supplies (reservoirs, rivers, and well fields) or from private wells in the region is reported by USGS to be relatively small because waste water is returned directly to the groundwater through on-lot septic management systems or as treated effluent discharged to rivers.

2.2 Regional Climate Data

Princeton Hydro compiled regional climate data sets from multiple observation stations located throughout the project setting. The primary data sets included daily temperature (minimum, maximum, mean) and precipitation measurements. Using the measured climate variables, Princeton Hydro calculated potential evapo-transpiration (PET) values on a daily basis using the Hargreaves – Samani (1982) method.

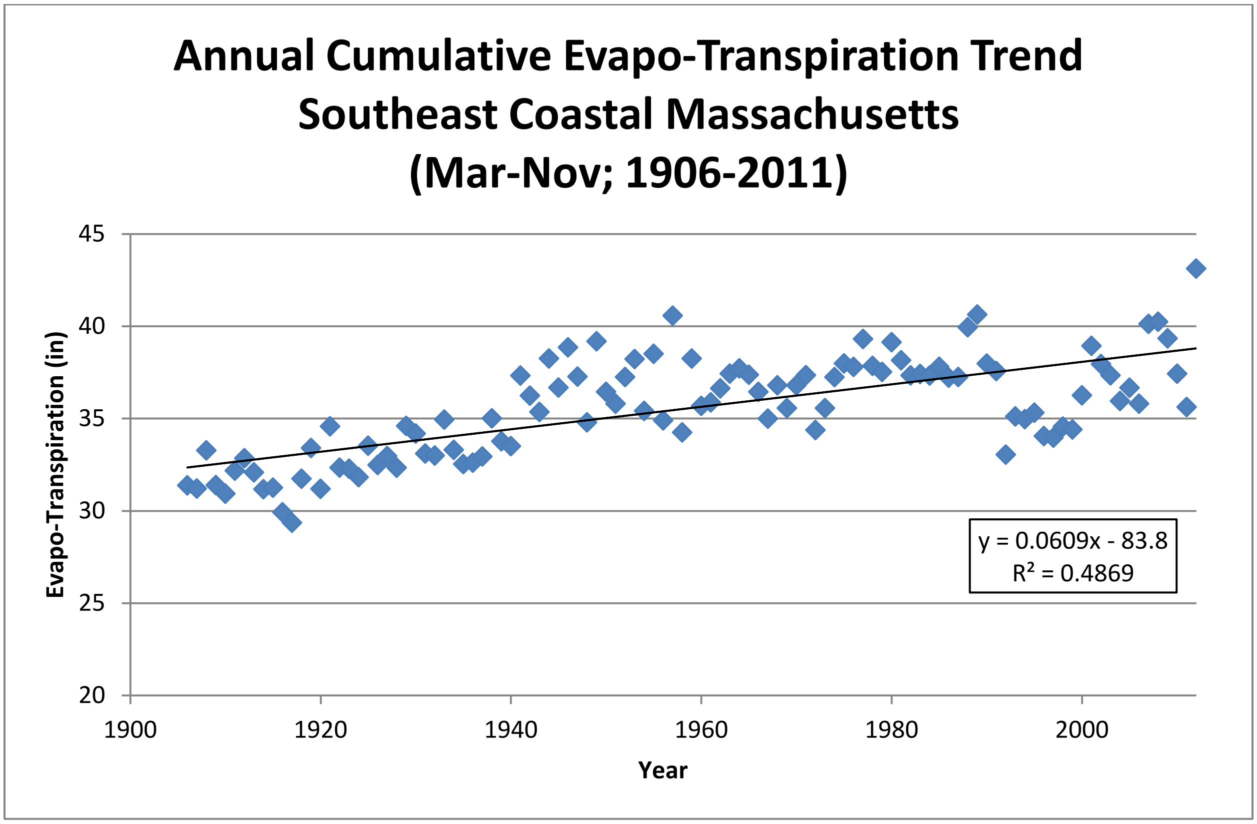


FIGURE 8. Chart showing total potential evapo-transpiration for Southeast Coastal Massachusetts for the months March – November spanning period 1906 to 2011.

To identify possible trends indicative of climate change that may be underway in the region, Princeton Hydro examined various time-series relationships related to temperature and precipitation. We assessed maximum, minimum, and average temperature on daily, monthly, seasonal, and annual time-step basis; monthly, seasonal, and annual precipitation; the frequency and length of precipitation – free periods on seasonal and annual basis; and, total PET for various assumed growing season periods.

Of the combinations of factors we evaluated, the time series of total PET calculated for the growing season exhibited the strongest correlation for a trend through time. As indicated by Figure 8, total calculated PET for the growing season (e.g., March through November), increased approximately 15% or more since the beginning of the 1900s.

2.3 Regional Water Budget

USGS (Masterson et al. 2009) calculated a simple regional water budget for the southeast coastal aquifer systems, expressed as:

Precipitation (P) – Evapotranspiration (ET) = Aquifer Recharge (R)

Using long-term (1931 – 2006) climate records from within the region, USGS reported average annual P as 47 inches and annual ET estimated to be 20 inches; therefore, as calculated above R equals 27 inches or approximately 57% of the region's average annual precipitation. Using stream flow measurements, USGS concluded that roughly 70% of the average annual recharge (~19 inches) for the region is expressed as stream base flow that is discharged to the estuary and another approximately 25% of recharge (6.8 inches) directly enters the coastal margin through the aquifer interface. The remaining 5% of annual recharge is equivalent to the water volume withdrawn from wells (Masterson et al. 2009).

In Section 1.3, charts of long-term monthly recharge, water table elevation, and stream flow were shown that demonstrated correlation among these three factors. Although groundwater systems (hydrologically) exhibit a time lag with respect to climate, the PCKD aquifer system is particularly vulnerable to drought. As evidenced by the regional water budget, 95% of annual recharge is discharged to the estuary as stream flow or as direct seepage through the aquifer/estuary interface. Additionally, because an extensive array of wetlands, ponds, and lakes is effectively embedded in the regional unconfined water table, ET processes efficiently remove water from the aquifer. Furthermore, the unconsolidated PCKD aquifer system is highly transmissive, meaning that water retention within the aquifer is brief; in other words, this aquifer stores water poorly. In periods of drought or in areas where water withdrawal rates are high, the PCKD may be readily depleted.

2.4 Brockton Water Supply System

Brockton's primary sources of potable water are located approximately 20 miles southeast of the City of Brockton, in the Towns of Halifax, Plympton, Kingston, and Pembroke (all of which, including Brockton are in Plymouth County). As indicated by the panel of USGS topographic maps below on Figure 9, the regional landscape exhibits long-standing human alteration. Review of the earliest map in Figure 9 illustrates the relatively sparse land development that existed in the water supply area prior to Brockton's use of Silver Lake. Subsequent maps show the pattern and density of land development in the BWS setting, including conversion of Great Cedar Swamp at the outlet of Monponsett Pond for cranberry production.

Others, notably Hanson-Murphy Associates (2006), provide a thorough description of the BWS system infrastructure. To recap in brief, beginning in 1905, Brockton began to pipe water from Silver Lake to the City for potable supply purposes because the City's Avon Reservoir lacked both the reliable capacity and water quality needed to satisfy Brockton's demands (Kasperson 1969). By the mid-1960s, Brockton's water demand exceeded the reliable yield of Silver Lake and in the late 1960s, diversions from Furnace Pond and Monponsett Pond into Silver Lake were constructed to augment the BWS system. In conjunction with the Furnace/Monponsett supplemental diversions, Brockton established fixed weir elevations for Furnace and Monponsett Ponds and also constructed a water filtration plant at Silver Lake. Prior to building the Silver Lake Water Treatment Plant (WTP), the raw water quality of Silver Lake as delivered to Brockton was suitable for potable use.

Abington, MA Sheet (USGS 1888) Hanover, MA (USGS 1962) Hanover, MA (USGS 2012)

FIGURE 9. Panel of USGS Topographic maps for the City of Brockton's principal water supply source area. The 1888 map pre-dates Brockton's diversion from Silver Lake; the 1962 map preceded Brockton's diversion of Monponsett and Furnace Pond into Silver Lake; and the 2012 map shows existing conditions.

3.0 WATER BUDGET for PRIMARY SOURCES in BWS SYSTEM

An understanding of the hydrology for each of the primary BWS sources is crucial to evaluating the complex dynamics of water management for Brockton's supply in the region. Hydrology also is the driving factor for understanding impacts to ecology and for developing management alternatives to the existing operations framework.

The BWS system hydrology is complex for various reasons. The primary reason is that water entering and departing Silver Lake is heavily manipulated through a series of withdrawals and multiple diversions of water from three separate watersheds and impounded basins. Moreover, water diversions into Silver Lake occur through a regulated "diversion season". Additionally, although on a large scale most water supplied for potable (as well as agricultural and industrial) use effectively remains within the regional hydrologic system via some mechanism of used-water return, the pattern is much different in the BWS project area. The BWS system moves finished water to Brockton, located outside of the Jones River watershed. Following its use in Brockton, wastewater is discharged into the Taunton River. But the diversion season for BWS operations includes periods for which water is moved across the Taunton River divide from Monponsett Pond and across the North River divide from Furnace Pond, into Silver Lake when the water surface elevation of Silver Lake is high enough to produce outflow into the Jones River.

3.1 Water Balance Approach

To properly gauge the magnitude of the BWS water manipulations and assess impacts to hydrology as well as water quality, and to identify ecological vulnerabilities, a water budget was developed for the three primary BWS source water bodies. Others (notably Masterson et al. 2009, as well as GZA 2003) developed hydrologic budgets for the region as well as parts of the study area that were based on models that estimated stream base flow as an expression of groundwater and included calculations of storm runoff. Princeton Hydro applied an alternative hydrology budget approach that relied on available flow data measured within the BWS system. BWS generously supplied Princeton Hydro with their water diversion spreadsheet used to maintain daily records that encompass 1996 through the present for Silver Lake stage, diversions from Monponsett Pond and Furnace Pond, and finished water delivery to Brockton. BWS's spreadsheet, and a second data set detailing lake stage in Monponsett Pond and Furnace Pond from 2009 through the present, contained most of the elements required to construct the water budget.

Princeton Hydro approached water budgets for this study as a mass balance exercise wherein hydrologic inputs balance hydrologic outputs. In general, hydrologic inputs into a lake include direct precipitation, tributary inflow (including base flow and runoff elements), surface runoff, groundwater, and diversion. Outputs include evapo-transpiration, tributary discharge, loss to groundwater, and withdrawals. One other component bears consideration, change in lake volume or storage, which can be significant, especially in managed systems. For a managed system such as Silver Lake, the change in storage term is significant because BWS maintains Silver Lake to be full or re-filling as practical to ensure that its customer demands are met.

Most of the water budget components are readily measured or calculated including direct precipitation, direct evaporation (estimated using the Thornthwaite equation for the New England region), tributary discharge, diversions, and withdrawals. Tributary discharge was calculated for Silver Lake to Jones River based on data included in the GZA report (2003) and re-iterated in the G&S report (2013) that was transformed from stage-discharge ratings curves and lake stage data. A similar approach was applied for Monponsett and Furnace Ponds. Both of these systems exhibit two components of tributary outflow; discharge through a fish way and discharge over a weir.

Small and ungauged tributary inflow is accounted for in our water budget approach in several ways; first by including all watershed areas identified as "water" in GIS data as part of the direct precipitation term. Second, the base flow component of tributary discharge into a lake is "captured" as part of a net residual groundwater flux term. Runoff is considered minimal and also is contained within the net groundwater term. Storage was calculated by examining monthly changes in lake stage and comparing changes to existing stage-storage curves or hypsographic data developed by Princeton Hydro using available bathymetry data.

The net groundwater term functions as a remainder for unmeasured and uncalculated components of the water balance equation as described above. As a net term, groundwater at steady-state condition, means influx and outflow are equal. However, manipulations of lake stage caused by diversions and withdrawals, paired with natural processes affecting lake volume, also implies that piezometric variability exists within the system, especially on short-term basis. Piezometric characterization was not available and is well beyond the scope of our work. But, considering net effects of groundwater flux for the particular water bodies in the BWS system provides useful context to understand the affects of BWS operation practices.

The Silver Lake hydrologic budget was calculated on a monthly basis using monthly average values for the water budget terms based on the period 1997 through 2012. For both Monponsett and Furnace Ponds, the monthly input data values reflect 2009 through 2012 (i.e., available data for lake stage). Differences in period of record explain the difference between certain common terms in the water budgets of the individual water bodies such as precipitation.

Each monthly budget resolved to zero; on an annual basis, the mass balance error was less than 2%. The BWS lake systems have inherent variability that mostly result from water manipulations and climate variability. The water budget terms are presented in the units of million gallons per month (MGM). The hydrologic budget equation for Silver Lake is provided below:

Inputs (including residual groundwater term) = Outputs +/- Storage Change

$$P_D + D_{M+F} + GW_{NET} = Q_{JR} + ET_D + W_{SL} +/- \Delta S$$

Where;

P_D = Direct Precipitation
D_{M+F} = Diversion from Monponsett and Furnace Ponds

GW_{Net} = Net Groundwater
Q_{JR} = Discharge to Jones River
ET_D = Direct Evapo-transpiration
W_{SL} = Finished Water Withdrawal from Silver Lake
ΔS = Change in Storage

The budgets for the other two watersheds, Monponsett Pond and Furnace Pond, utilize the same basic equation; however, specific terms are unique to Silver Lake and do not apply to the other BWS lakes or are opposites.

A summary of each of the three watersheds is provided below.

TABLE 1. Summary Statistics for Key Component Sources of Brockton Water Supply System

Metric	Units	Silver Lake	Monponsett Pond East	Monponsett Pond West	Monponsett Pond Total	Furnace Pond and Oldham Pond
Lake Area	ha	256.71	110.79	125.14	235.93	143.26
	acres	634.34	273.77	309.23	582.99	354.00
Lake Volume	Mm^3	19.40	2.04	2.61	4.65	2.84
	MG	5,124.06	537.78	689.55	1,227.81	749.96
Average Depth	m	7.55	1.84	2.09	1.97	1.98
	feet	24.77	6.04	6.84	6.46	6.50
Watershed	ha	1,102.74	899.80	832.92	1,732.72	675.14
	acres	2,724.91	2,223.44	2,058.18	4,281.63	1,668.31
Area of Water in Watershed	ha	266.20			305.03	144.81
	acres	657.79			753.73	357.82
Watershed Area minus Area of Water	ha	836.54			1,427.70	530.34
	acres	2,067.12			3,527.89	1,310.49

Silver Lake is the largest lake in the BWS system by area and particularly by volume (owing to its depth). The Monponsett Pond watershed is the largest studied and also has the greatest water surface area, including not only both basins of Monponsett Pond, but a series of other smaller ponds and lakes throughout the watershed; the largest of which is Stetson Pond. The Furnace Pond watershed, which includes the larger Oldham Pond, is the smallest unit in the BWS system, and the combined volume of Furnace and Oldham Ponds, which share a common stage and are treated as a single unit for modeling purposes, is significantly less than either Silver Lake or Monponsett Pond. While the size of the watersheds and the lakes vary, Monponsett Pond and Furnace/Oldham Pond are rather similar in many respects including general morphology (average depth is approximately 6 – 7 feet for both lakes), position in the landscape, level of shoreline development, and maintaining a steady, if low discharge to their outlets; Stump Brook and Herring Brook, respectively.

3.2 Water Balance Summaries for Brockton Water Supply Sources

The following charts depict the monthly water balance terms for each watershed in the BWS system. As described above, the Silver Lake budget is based on data from 1997 through 2012 while the other two watersheds were based on empirical data collected from 2009 through 2012. The shorter period of record therefore is more prone to deviation when compared to a longer-term central tendency, especially as it relates to highly variable climate data. Note that the average annual precipitation was nearly 7.5 inches greater in the shorter term record, a fact driven by several months of above-normal precipitation events including over 14 inches in March 2010 and to a lesser extent, a series of tropical and extra-tropical storms in the autumns of 2011 and 2012. The above-normal precipitation is reflected as a pulse of water through the system in the spring of 2010 with lingering effects on the monthly average throughout this period highlighted by high discharges through the outlets and groundwater movement.

The budgets summarized below (Figure 10) also indicate differences in the hydrologic framework of each lake. The most notable pattern relates to the artificial manipulation of water movements through the lakes. While all lakes are net exporters to the BWS system; directly in the case of Silver Lake and indirectly for Monponsett Pond and Furnace Pond, Silver Lake is the only water body that receives diversions as inputs. Stated differently, the finished water delivered to Brockton from Silver Lake is artificially supplemented by diversions from Monponsett Pond and Furnace Pond.

In fact, the diversions from Monponsett Pond and Furnace Pond are equivalent to more than 76% of the water delivered to Brockton from Silver Lake over the course of a year (Figure 11). While this accounting form simplifies the complexities of the system, the point demonstrates that much of the BWS demand is subsidized by contributions to Silver Lake by Monponsett Pond and to a lesser extent Furnace Pond.

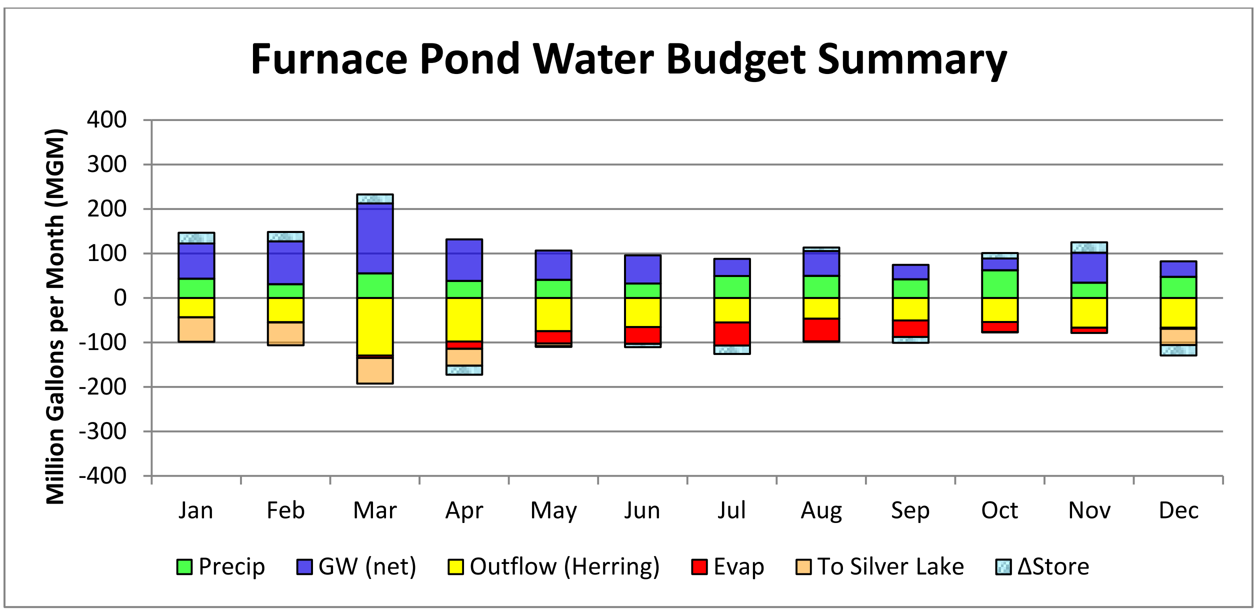
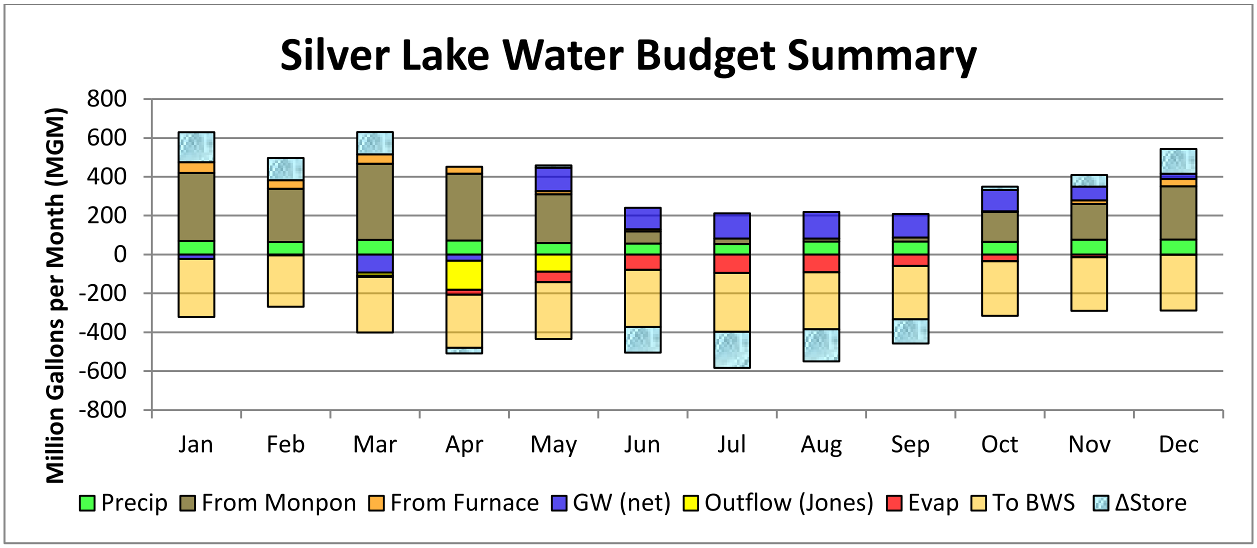


FIGURE 10 (A). Summary charts of monthly water budget terms for the Brockton Water Supply system.



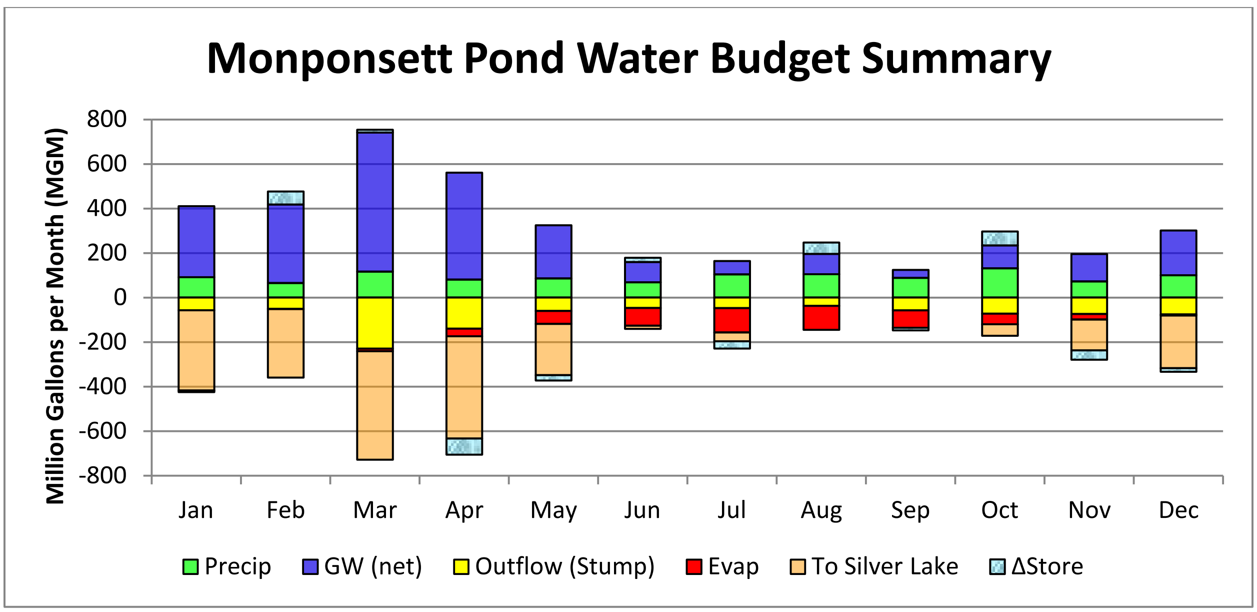


FIGURE 10 (B-C). Summary charts of monthly water budget terms for the Brockton Water Supply system.

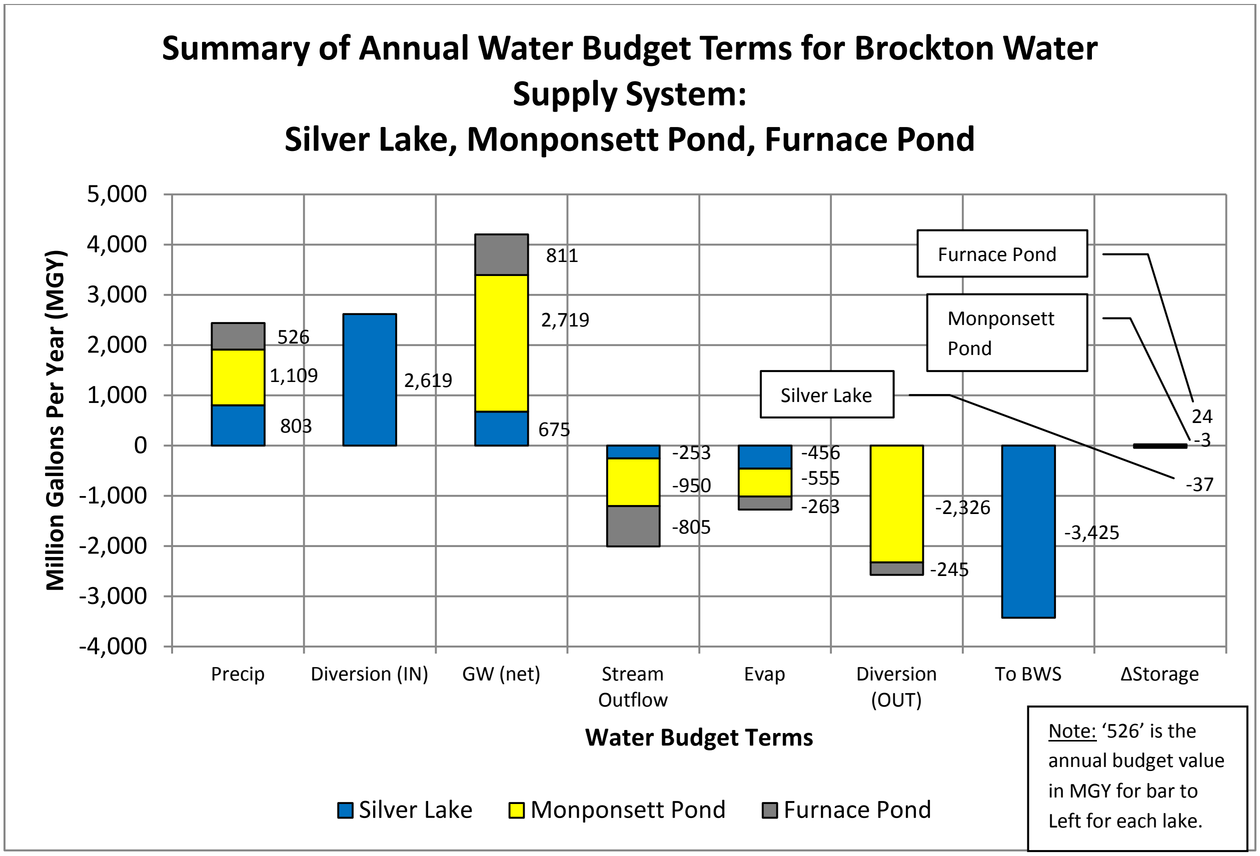


FIGURE 11. Summary annual water budget terms for the Brockton Water Supply system's primary water body sources. Note that Output budget terms are indicated by negative MGY values.

The pattern of contribution in the BWS system becomes starker when examined on an average monthly basis in terms of the diversions and withdrawals for Silver Lake. Combined diversions from Monponsett Pond and Furnace Pond meet or exceed the total water withdrawal from Silver Lake from December through May (Figure 12). Furthermore, the transfer of water from Monponsett and Furnace Ponds into Silver Lake is not offset by supplemental inputs to these contributing sources as it is in Silver Lake. Overall the artificial transfer of water across natural divides establishes two functional groups according to hydrologic regime as discussed below.

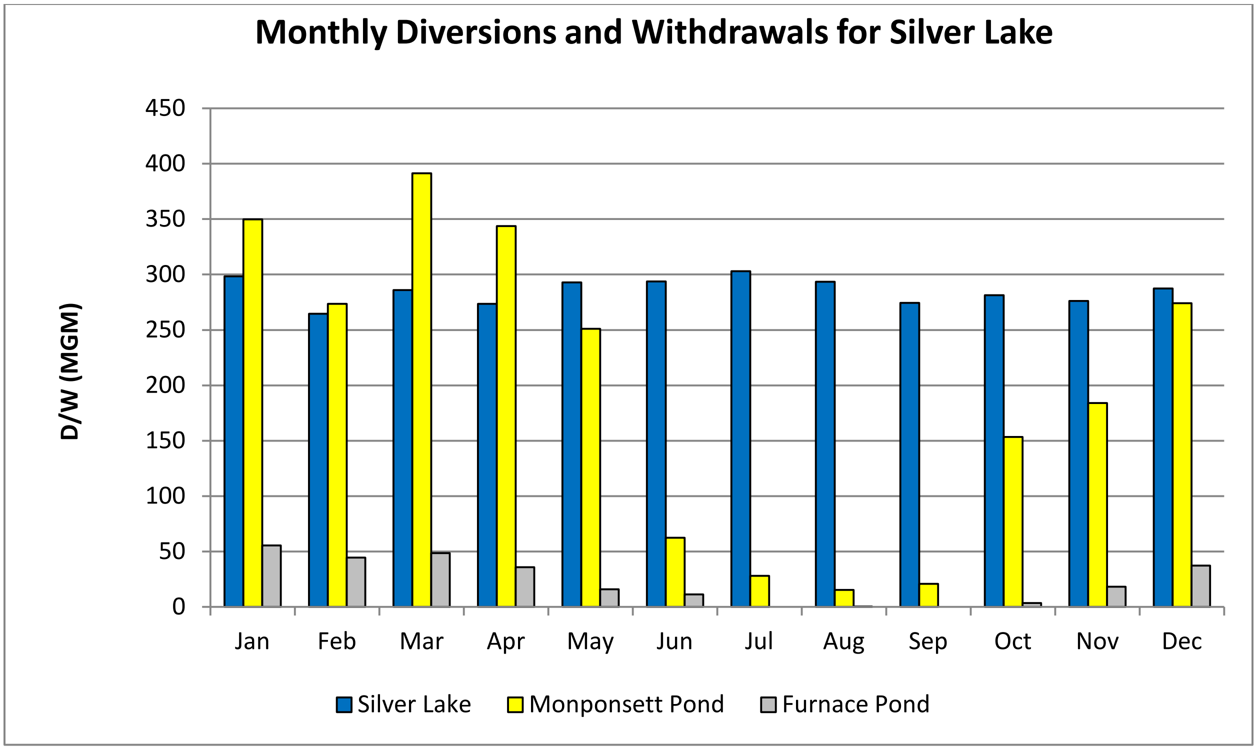


FIGURE 12. Summary of average monthly water diverted to and withdrawn from Silver Lake in million gallons per month. Note that BWS periodically diverts water from Monponsett Pond to Silver Lake outside the diversion season in response to concerns about flooding impacts.

3.3 Functional Hydrologic Differences for Brockton Water Supply Sources

Monponsett and Furnace Ponds both exhibit net groundwater gains for every month throughout the year; whereas, on balance, groundwater is lost from Silver Lake from January through April. Similar to the regional patterns for stream discharge, groundwater elevation, and ET (Figure 3), the contribution of groundwater to these lakes exhibits a natural pattern defined by peak flows in the spring, followed by decreasing contributions through the summer to a low point typically reached in September – October, and eventual recovery through the late fall and into the winter.

Silver Lake exhibits a decidedly unnatural flow pattern for groundwater through the system. First, there is a complicated series of interactions between the lake and the surrounding groundwater table. The net movement of water from Silver Lake to groundwater in late winter and early spring likely is the result of diversion practices in the system. The relatively rapid filling of the lake through the regulatory diversion window of late fall through spring is driven in large part by water diverted from Monponsett Pond and Furnace Pond. This circumstance likely leads to lake stage that is above the adjacent groundwater table. Owing to piezometric gradient, water within the Silver Lake basin leaks through the lake bed into the surrounding stratified drift deposit materials (Figure 13C).

At a point, net groundwater flux is neutral, thereby facilitating two-way exchange of groundwater into and out of Silver Lake (Figure 13A). At some point after the regulated diversion season ends, the constant withdrawal of water through the Silver Lake Treatment Plant, coupled with the increased seasonal evaporation demand, again shifts the piezometric gradient. At this point (Figure 13B), groundwater enters the lake on a net basis.

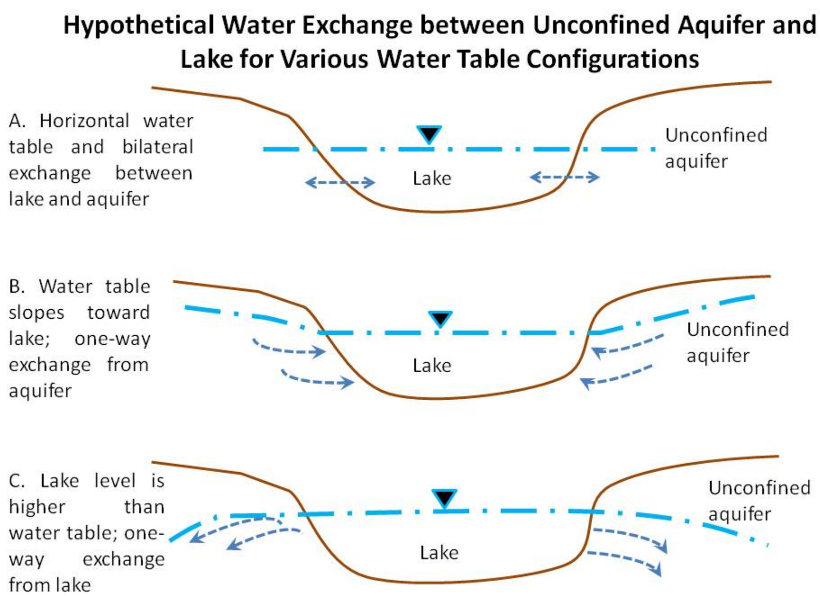


FIGURE 13. Sketch showing simplified water exchange scenarios between a lake and unconfined aquifer due to variable positions of the water table.

Groundwater flows also are affected by seasonal depth to the water table that oscillates in response to the ET pattern throughout the year.

The difference in groundwater contributions between Monponsett Pond and Furnace Pond are roughly equivalent to the ratio of lake surface area to watershed catchment area. Groundwater contributions to Silver Lake are much different than the other two ponds. Rather than exhibiting a seasonal variable groundwater flux in the shape of a sine wave with a peak in the spring, Silver Lake has a more modal state dominated by a net loss to groundwater from January through April followed by a phase shift starting in May and lasting through October when there is a large and very stable influx of groundwater to the reservoir, followed by a decreased influx in November and December.

Another factor that supports the established grouping of these lakes is discharge to their respective tributaries. Both Monponsett Pond and Furnace Pond maintain discharge through their outlets throughout the year (albeit, flows are reduced during periods of diversion); while Silver Lake discharges to the Jones River reliably only during March, April, and May (Figure 14). Moreover, discharge through all of the outlets is managed by a variety of water control structures that include dams, weirs, fish ladders, and/or low-level gate valves.

Overall, discharge to both Stump Brook and Herring Brook follows generally natural patterns with peaks in the spring that quickly decline through the summer as evapo-transpiration increases, and a recovery period in the fall months. While the patterns are consistent with natural flow regimes, the average discharge is fairly low given the size of the watersheds, particularly for Monponsett Pond/Stump Brook, where most of the water being shunted to Silver Lake otherwise likely would be expressed as discharge to Stump Brook. In contrast, discharge from Silver Lake to Jones River is entirely unnatural, and connection flows from Silver Lake into Jones River only occur for a brief portion of spring and even then, at modest flow rate. Unsurprisingly, discharge into Jones River coincides with peak diversions from Monponsett Pond and Furnace Pond into Silver Lake.

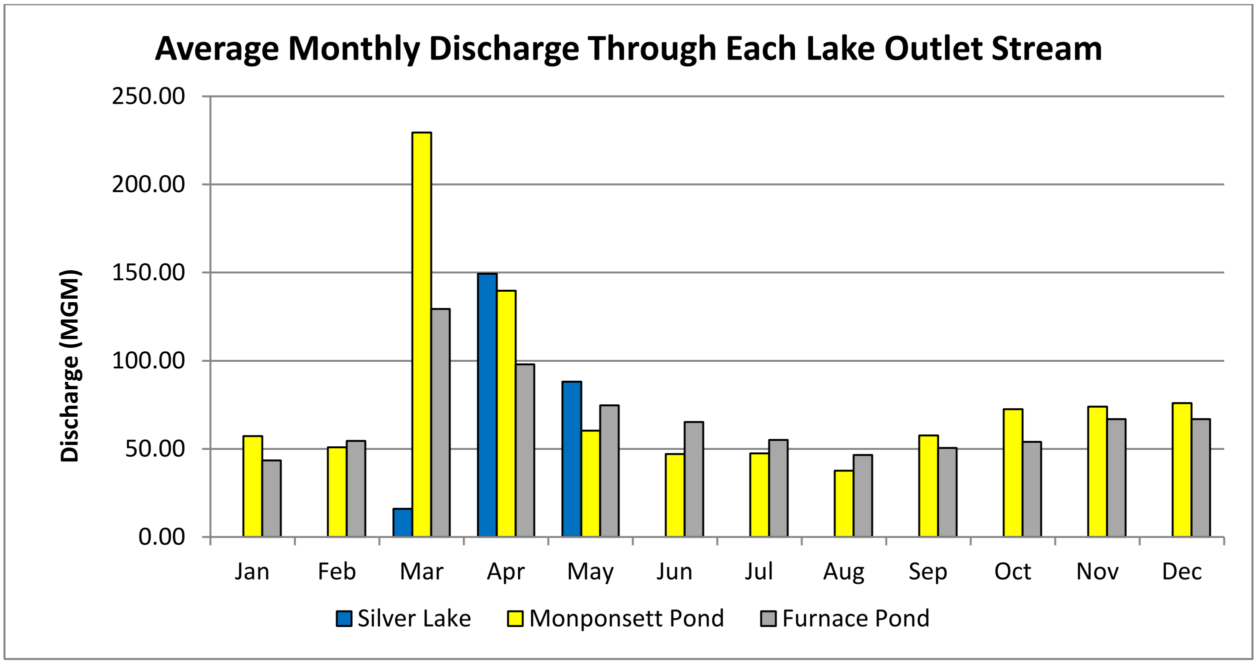


FIGURE 14. Summary of average monthly discharge to outlet streams for the primary sources in Brockton Water Supply system.

3.4 Water Budget Summary

To summarize, hydrology in the BWS system is complex due primarily to artificial manipulation required to meet water supply demands. In short, the water budget exercises demonstrated several patterns that contradict natural flow regime. Several facts neatly demonstrate the degree of manipulation in the system, the impacts of the manipulation, and invariably question the sustainability of current withdrawal and diversion practices.

First, and by coincidence, BWS's delivery of treated water from Silver Lake is roughly equivalent to the sum total of all precipitation that enters the approximately 4.3-square mile Silver Lake watershed in a year. This point is noteworthy: more water is withdrawn from Silver Lake and transported for use in Brockton than is available in Silver Lake's natural watershed. The fact that more water is delivered by BWS from Silver Lake than the natural hydrology can support is the basis for the various water management crises that erupted during episodes of severe drought in the 1960s and 1980s.

On a chronic basis, BWS' reliance on Silver Lake water produces a flow deficit for its outlet, Jones River. For extended periods (June through February), there is intermittent or no flow from Silver Lake to the upper reaches of Jones River.

The over-allocation of Silver Lake's natural carrying capacity was revealed in crisis form in the 1960s and again in the 1980s. The turmoil borne of crises forced water supply managers to divert water from neighboring watersheds. Annually, over 2,600 MG of water is diverted into Silver Lake from Monponsett Pond and Furnace Pond combined – in the past, water also was diverted from Pine Brook during emergency circumstances. Based on our calculations, diversions to Silver Lake account for more than 60% of Monponsett Pond's total annual water budget. Amongst other impacts discussed in the next sections, the hydrologic strain on Monponsett Pond results in reduced outflow to Stump Brook, the natural outlet of Monponsett Pond. Based on the water balance approach, we estimate that Stump Brook flow is currently less than 1/3 of its potential annual discharge.

4.0 POLLUTANT LOAD ANALYSIS for PRIMARY SOURCES in BWS SYSTEM

Princeton Hydro conducted a pollutant load analysis for the project area to provide a means of evaluating the effect of land development/land use in the three watersheds, as well the impact of water management practice on resources. Pollutant loading in this context more properly refers to macronutrient loading. Nutrient pollutants, particularly phosphorus (P), are typically responsible for many of the adverse impacts to water quality; usually due directly or indirectly to increased algae and aquatic macrophyte (plant) growth.

4.1 Implications of Nutrient Loading in Aquatic Settings

P is generally the limiting nutrient in most water bodies meaning that it is the nutrient in shortest supply relative to biological demand. As a result, small additions of P can have deleterious effects and abruptly spur biological activity that often results in algae blooms as well as nuisance plant growth. The major growth cycles related to P-enrichment are often attended by a host of associated issues including reduced dissolved oxygen concentration, fish kills, diminished water clarity, impairments to aesthetics (odor/taste/visual quality), loss of recreational uses, and of increasing concern to water quality managers and regulators, the production of cyano-toxins that can impart serious health impacts, occasionally lethal, to contact users and wildlife.

In addition to impacts on ecology and recreational use, there can be a substantial impact to water suppliers that is attributable to P-enrichment. Increased biological activity can lead to issues of taste and odor, increased microbial loads, and increased suspended solids concentrations, all of which require enhanced treatment methods and at a minimum, warrant more frequent backwash of the intake filters.

Increased nutrient loading and increased primary production attributed to algae and plants is referred to as eutrophication. While eutrophication is a natural phenomenon, in a natural setting it proceeds at a geological pace. In developed watersheds; however, the increased nutrient loading and aquatic response is typically termed *cultural eutrophication*; a phrase that indicates an anthropogenic role.

The developed land proportion of a watershed, including agricultural lands, as well as any land use that deviates from the natural state[6], is subject to increased nutrient loading. There are a wide variety of sources of nutrient pollution usually grouped into two broad categories including point source (PS) and non-point source (NPS). PS pollution generally refers to a piped or otherwise discrete discharge; and with respect to nutrient loading, PS is mostly attributable to wastewater treatment plants. While there are regulations governing effluent concentrations for a host of analytes, even compliance with regulatory standards can represent a significant increase in P loading rates compared to natural conditions.

NPS loading tends to be of greater importance in many watersheds because they encompass the remainder of loading, are thus diverse and difficult to manage, and frequently the magnitude of NPS loading far exceeds that of PS loading. Overland runoff tends to be one of the more important forms of

[6] Primarily mixed deciduous/coniferous forest in this region.

NPS loading because it mobilizes particulate as well as soluble forms of nutrients including soil particles (a major source of P loading is adsorbed to particles), fertilizers, organic detritus, and livestock and wildlife waste.

Nutrient loading also tends to increase with increased impervious coverage or with the general level of site disturbance due to decreased infiltration and increased runoff and erosion. Another significant source of NPS loading includes on-site septic systems. While septic systems can provide a high level of treatment, especially for some chemical forms of P, they tend to perform more poorly for nitrogen (N) pollutants which may be extremely water-soluble and thus move easily within groundwater. Septic system treatment efficiency can be substantially impacted by the geotechnical characteristics of soils as well as by a high water table. In particular, lakeside development coupled with soils that exhibit high hydraulic transmissivity tend to under-perform in terms of septic treatment efficacy. Another significant form of nutrient loading is atmospheric loading related to the settling of dry airborne particles as well as substances dissolved in rain water. Atmospheric nutrient inputs tend to be dominated by nitrogen (N) rather than P. Major sources of N in atmospheric loads are N-oxides derived from vehicle exhaust and power plant emissions.

4.2 Nutrient Load Analysis for Brockton Water Supply Sources

While PS and NPS components generally represent the sum of nutrient loading in most watersheds, the annual transfer of more than 2,600 MG from Monponsett and Furnace Ponds has the potential to add significantly to P loading in Silver Lake. Note that manipulation of water in the three basins *per se* has little impact on P loading except for Silver Lake because nutrient loads will not be directly altered in Monponsett or Furnace Ponds by withdrawals. This statement does not mean that there is not a trophic response in primary productivity because biological assimilation of nutrients is dependent not only on simple nutrient loading, but also on the hydrology of the system. The complex interactions between nutrient loading – hydrology – and trophic response will be described in more detail in the Trophic State Model section. The bulk of findings regarding this pollutant loading analysis is developed as a primary factor for use in the Trophic State Models that will facilitate an evaluation of pollutant loads in the BWS setting.

The development of a pollutant budget for the project area was performed only for the limiting nutrient P using the Unit Area Load (UAL) model published by the USEPA (Uttormark et al., 1974). This simple, yet robust model calculates pollutant loads by multiplying loading coefficients for specific land use/land cover (LU/LC) types. Coefficients used herein were derived primarily from three main sources including the Uttormark (1974) work, Reckhow et al. 1980, and the USEPA *Protocol for Developing Nutrient TMDLs*.

A conservative approach[7] was taken in selecting coefficients because the nutrient content of the region's sandy glacial soils is assumed to be low and because erosional forces that tend to mobilize soil particles as well as the total volume of runoff generated from the watershed, both critical elements of pollutant loading, are assumed to be low due to the high infiltration rates as discussed previously. Two

[7] Herein, the term ***conservative*** means assumptions that likely underestimated nutrient inputs.

additional sources were reviewed to characterize nutrient loading from cranberry bogs, which are an important component of land use in the project setting; i.e., Howes and Teal 1995, and DeMoranville and Howes 2005. The list of loading coefficients is provided below.

TABLE 2. Summary Phosphorus Coefficients used in Nutrient Loading Model of Brockton Water Supply System

Phosphorus Loading Coefficients			
LU/LC Type	kg/ha/yr	LU/LC Type	kg/ha/yr
Brushland/Succcessional	0.17	Non-forested wetland	0.00
Cemetary	1.83	Nursery	2.31
Commercial	0.78	Open Land	0.44
Cranberry Bog	9.90	Orchard	0.55
Cropland	3.07	Participation Recreation	0.91
Forest	0.17	Pasture	1.08
Forested Wetland	0.00	Powerline/Utility	0.62
Golf Course	1.57	Saltwater Sandy Beach	0.00
High Density Residential	1.02	Saltwater Wetland	0.00
Industrial	1.90	Transitional	0.77
Junkyard	1.90	Transportation	1.10
Low Density Residential	0.82	Urban/Public Institution	0.90
Medium Density	0.90	Very Low Density Residential	0.30
Mining	2.14	Water	0.00
Multifamily Residential	0.97	Water-Based Recreation	0.55

Several other components were considered including an atmospheric load attributed to all water bodies based on the loading coefficient of Reckhow et al. 1980. A septic load also was calculated for each individual watershed. Following the approach MADEP applied to develop the White Island Pond[8] Total Maximum Daily Load (TMDL), the septic load was limited to dwellings within a buffer on each of the major lakes; while the TMDL used a 100 meter buffer, Princeton Hydro applied a more conservative approach. In this study, only houses or septic fields within approximately 100 feet of the shoreline were included in the loading analysis.

Dwellings were identified and enumerated based on review of aerial photographs. Shoreline development density is fairly high in parts of the project region. Silver Lake had approximately 24 housing units within the setback, which attests to efforts to protect the watershed and water quality of the lake. On the Furnace Pond system, including Oldham Pond, Gorham Mill Pond, and Furnace Pond there are approximately 235 units and on the east and west basin of Monponsett Pond and Stetson Pond there were 243 dwellings. After the houses were counted a population estimate was derived using US Census Bureau data for the average number of household residents in each municipality. A weighted average based on approximate shoreline coverage was used where the shoreline extended over multiple municipalities. Once the total population was calculated this was multiplied by a per capita rate. While Uttormark lists a coefficient for per capita total P (TP) loading, the age of the reference; i.e., 1974, pre-dated most of P detergent bans and thus is considered excessively high. An average loading

[8] White Island Pond is headwaters to Red Brook, another small coastal area river located in Plymouth County, MA that is underlain by the PCKD aquifer system.

rate of 0.114 kg TP per capita was used instead, taken from the New York State Department of Environmental Conservation (NYSDEC) *Impaired Waters Restoration Plan for Greenwood Lake (*2005*).*

One potentially sizeable load that was not factored directly in our calculus was an internal cycling. Internal nutrient cycling refers to the release of P that is bound in sediment; usually in a complex with iron. P release from sediment occurs under oxic conditions at a relatively slow rate, but when the hypolimnion of a lake becomes anoxic this creates a dramatic shift in the geochemical oxidation-reduction potential, thereby releasing P at a rate an order of magnitude higher than under oxic conditions. Formation of anoxia in eutrophic systems may create a positive feedback cycle; while initial algae blooms can cause anoxia in the deep water upon senescence. Following settling of large pulses of organic material to the sediment, the subsequent release of P at anoxic conditions can spark additional algae blooms. While internal nutrient loading has been raised as a potential issue in Monponsett Pond, the shallow morphometry of the pond and relatively brief periods of hypoxia or anoxia, coupled with a June 2013 alum treatment, probably minimize effects of internal loading. Similar rationale holds for the Furnace Pond system.

Although Silver Lake undoubtedly stratifies as was reported in the ***Silver Lake Water Quality Assessment Report*** (ESS 2004), mixing dynamics are not well known and without a breakdown in stratification or a mixing event, the generated loads likely remain biologically-unavailable below the photic zone or the surface band of algal activity. Even for the deep sub-basins within Silver Lake, turn-over dynamics that adhere to typical seasonal patterns are not expected to be problematic. The deep zones of Silver Lake likely exhibit seasonal hypoxia as a natural phenomenon. Typically, turn-over occurs in spring and fall and nutrients made available during turn-over are rapidly used in spring to facilitate growth by early season phyto-activity or are discharged concurrent with annual high lake stage and tributary outflow. However, fall turn-over events tend not to stimulate much algae growth because seasonal demand is naturally low and high DO concentrations with lower water temperatures precipitate the P.

P loading also was calculated for water that enters Silver Lake due to diversions from Monponsett Pond and Furnace Pond. An average TP concentration in diverted water was based on values reported from several studies then weighted by the average annual diversion volume.

A summary of the P budgets for each of the primary watersheds in the BWS system is provided below in Table 3. Monponsett Pond has the largest pollutant load at over 2,400 kg of TP per year, followed by Silver Lake, and lastly by the Furnace Pond watershed. Moreover, the west basin of Monponsett Pond exhibited the single largest basin load. For the most part, the P loads are correlated with watershed area, but this correlation is not perfect and represents some real differences in pollutant loading dynamics between the watersheds. The series of charts in Figure 15 show the component load breakdown in detail for each major lake in the BWS system.

TABLE 3. Summary of Annual Phosphorus Load Budgets for the Brockton Water Supply System

Load	Units	Silver Lake	Monponsett Pond			Furnace Pond and Oldham
			East	West	Total	
UAL	kg	633.64	956.12	1,306.33	2,262.45	422.38
	%	60.55	90.47	95.08	93.07	77.59
Atmosphere	kg	79.86	51.50	40.01	91.51	43.44
	%	7.63	4.87	2.91	3.76	7.98
Septic	kg	7.85	49.25	27.60	76.85	78.57
	%	0.75	4.66	2.01	3.16	14.43
Diversion	kg	325.08	0.00	0.00	0.00	0.00
	%	31.07	0.00	0.00	0.00	0.00
Total	kg	1,046.43	1,056.87	1,373.94	2,430.80	544.39

As depicted in Figure 15, the annual P loads calculated for the primary water sources vary considerably, from approximately 550 kg (Furnace Pond) to more than 2,400 kg (Monponsett Pond). In terms of P loading inputs, the single factor that distinguishes pollutant loading dynamics in this system overall is the P load diverted into Silver Lake from Monponsett Pond and Furnace Pond which combined, accounts for over 30% of the total P load in Silver Lake. On a watershed area-adjusted basis, P loading to each of the primary BWS source lakes ranges from approximately 200 kg P/mi^2-yr for Furnace Pond to more than 350 kg P/mi^2-yr for Monponsett Pond. If the P loading fraction due to BWS diversion practices into Silver Lake is excluded from the nutrient budget, then P loading to Silver Lake is reduced to approximately 170 kg P/mi^2-yr.

While the NPS fraction represented by the UAL is the largest loading element to the system overall, it is notable that nearly a third of all P loading to Silver Lake originates outside the Silver Lake watershed and is delivered to Silver Lake by diversions. It also is interesting to note that the septic load is minimal in Silver Lake, and as mentioned previously, this fact represents sensible land use planning that minimized lakeside development and subsequent impacts to a Class A public water supply.

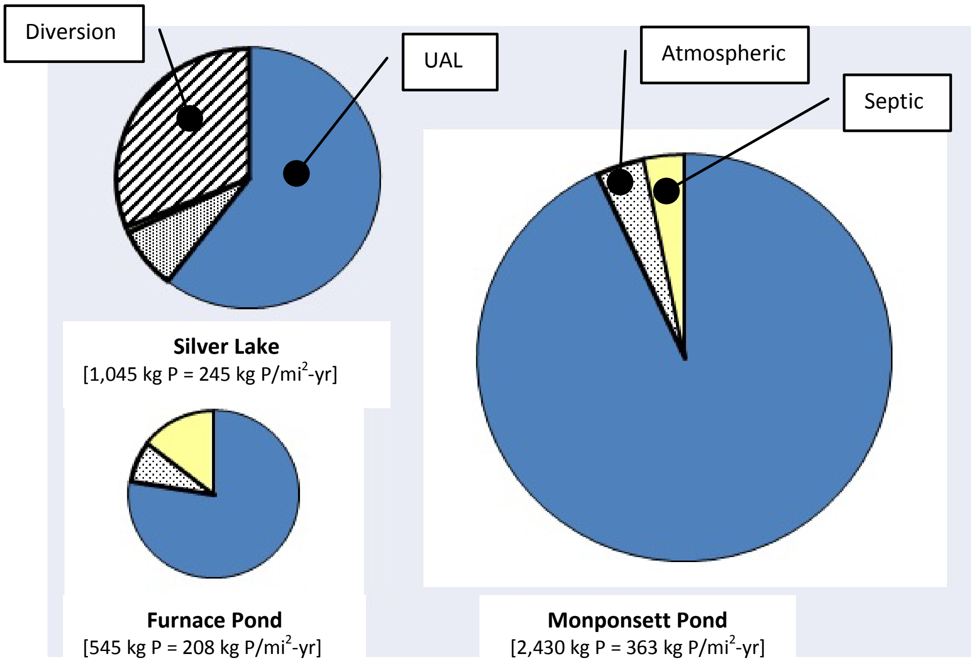


FIGURE 15. Summary charts that depict annual P loading allocation within each of the primary sources in the Brockton Water Supply system according to Unit Area Load (UAL), atmospheric, septic, and diversion sources. Each chart is sized according to that lake's estimated annual total P load. Total annual P load (kg) and watershed area weighted P loading rate (kg P/mi^2-yr) are indicated for each lake.

Furnace Pond has the lowest overall P load, but the highest component fraction as septic load due to the density of shoreline development. The overall housing density is about the same for Furnace Pond as it is for Monponsett Pond, but the septic load accounts for a smaller percentage of the total load in Monponsett Pond as a consequence of both a larger watershed and of specific LU/LC types in the watershed, especially cranberry production. Cranberry operations in the Monponsett Pond watershed are calculated to contribute approximately 78% of the UAL load in Monponsett Pond, while only accounting for about 38% in the Furnace Pond watershed.

5.0 TROPHIC STATE MODELING

Trophic state modeling conducted for this study provides a means to synthesize the effects of hydrology and nutrient loading within an aquatic setting. Trophic state refers to the level of primary productivity in lentic ecosystems such as lakes and ponds. Productivity is a measurement of the biological growth or activity of primary producers like algae and macrophyte plants that form the base of the trophic web in these ecosystems. Primary producers are autotrophic organisms that photosynthesize and fix carbon to increase organic content. In lakes, primary production (e.g., growth), particularly for algae, is most strongly correlated with nutrient concentrations in bioavailable forms. Using P concentrations as a proxy for primary production or trophic state relies on well-established correlations between nutrient concentrations and primary production.

Trophic state models are used to predict TP concentrations using both pollutant load data and hydrology budget information, which can consist of modeled, empirical, or mixed data. The integration of these two elements, hydrology and nutrient loading, represents the two basic forces that influence trophic state. Trophic state describes the balance between hydrologic inputs and pollutant loading. Higher flows, be they surface or groundwater, usually carry higher nutrient loads as a result of increased watershed area, the retention of nutrients in systems decreases with higher flushing rates as does biological assimilation and ultimately trophic response. The opposite also is true and systems with decreased flushing rates and pollutant loads, coupled with higher nutrient retention and biological assimilation may result in an increase in trophic response to nutrient loading.

Trophic state modeling was conducted for three primary purposes in this study. First, it is used to calibrate and validate our estimated hydrologic and P budgets. Second, it is used to describe the current trophic state of each of the component lake systems in the BWS array. Last, it is used in a predictive capacity to evaluate different loading scenarios and management alternatives for the manipulation of water throughout the three watersheds. This third purpose facilitates an informed review of impacts to an ecosystem and how such impacts may be better managed to meet various user-demands for the system; including the maintenance of water supply, the support of ecological communities, as well as hydrologic functions.

5.1 Trophic State Modeling Approach

A variety of trophic state models were used and evaluated for this analysis. Each of these models was developed under a differing set of lake/watershed characteristics and response is typically weighted more heavily towards one factor; half of the models are more sensitive to hydrologic inputs while the remainder are more sensitive to pollutant loading. As such, the results are reported as averages of the four models used. For the most part, the models contain the same few input terms arranged in different mathematical functions. The terms are as follows:

P = Phosphorus concentration, mg P/m^3 or ppb
L = Phosphorus loading rate, mg P/m^2
Z = Mean depth, m

T = hydraulic residence period

The models include:

Vollenweider, 1975: $P = L / (10 + Z/T)$

Larson and Mercier, 1975: $P = (LT / Z)(1 - R_p)$, where $R_p = 1/(1 + 1/T)$

Jones and Bachman, 1976: $P = 0.84\,L / (Z(0.65 + 1/T))$

Kirchner and Dillon, 1975: $P = (LT / Z)(1 – R_p)$, where $R_p = 0.426^{(-0.271(Z/T))} + 0.574^{(-0.00949(Z/T))}$

These models were largely developed in large watersheds with large reservoirs that exhibit low flushing rates (i.e., long residence time). Shallow, rapidly-flushed lake systems such as Furnace Pond and Monponsett Pond tend to evoke widely varying responses among the individual models. In contrast, Silver Lake which is much closer in morphometric and hydrologic features to the lakes upon which the models were developed and as a result, model agreement with observed data is much tighter.

Prior to initiating the modeling runs, a summary of water quality was prepared. Despite the abundance of studies conducted throughout the project area, there is relatively little water quality data and moreover, the data tend to be relatively old or the studies of brief duration. Of the three water bodies, Monponsett Pond is the best and most consistently studied as a result of the on-going and severe impairments of this system. Notably, Silver Lake is poorly studied and even the Comprehensive Water Management Plan (CDM, 2009) did not mention P or nutrients once in the entirety of the report.

A summary of available water quality parameter data is provided below. Each of BWS water bodies are moderately to highly productive. Systems with average TP concentrations in excess of 0.02 to 0.03 mg/L are usually considered eutrophic. Silver Lake is on the margin of eutrophy and is considered mesotrophic or of moderate productivity, although the maximum measured TP concentration of 0.06 mg/L is elevated. The west basin of Monponsett Pond is hyper-eutrophic and subject to severe nuisance algae growth. Furnace Pond also is squarely eutrophic.

TABLE 4. Summary of Available Total Phosphorus Concentration Values for the Brockton Water Supply System

		Silver Lake	Monponsett Pond			Furnace Pond
			East	West	Total	
Minimum	mg/L	Below Reporting Limits	0.020	0.049	0.020	0.010
Maximum	mg/L	0.060	0.070	0.705	0.705	0.195
Average	mg/L	0.020	0.032	0.134	0.107	0.047
References		1,2,3,4		2,5		6
1		Silver Lake Water Quality Assessment, ESS 2004				
2		Silver Lake System Overview Report, HMA 2006				
3		Silver Lake & Jones River Watershed Study, Teal 2000				
4		Draft River Herring Spawning and Nursery Habitat Assessment Silver Lake, Division of Marine Fisheries 2013				
5		Various Water Quality Reports, Lycott 2001 through 2011				
6		Diagnostic/Feasibility Study of the Pembroke Ponds, BEC 1993				

5.2 Trophic State Modeling Simulation Results

Silver Lake

The available P and hydrologic data were entered into the various trophic state models according to four simulation scenarios for Silver Lake; the mean modeled hydrology predicted TP value was 0.031 mg/L for current conditions. The mean predicted TP value was approximately 50% higher than the reported average, yet within the observed range (Tables 4 and 5). Since modeled groundwater through Silver Lake seemed to be underreported, groundwater recharge was substituted for the net groundwater term in the hydrologic budget and rerun through the models yielding an average phosphorus concentration of 0.026 mg/L (range: 0.023 mg/L to 0.028 mg/L; refer to Table 5). This predicted value is approximately 25% higher than the mean observed value but much closer than the initial estimate and suggests that actual groundwater flux into the Silver Lake system was higher than shown by the net groundwater term in our water balance model. The result also suggests that either the P budget may be slightly overestimated or that some mitigating factor exists in the watershed. One possibility is that deep water parts of Silver Lake were not adequately represented in the sampling scheme or that natural soil characteristics such as high iron concentration may bind P. While the agreement is not perfect, for planning-level exercises the result provides valuable information and again shows Silver Lake trending towards eutrophy in a system which formerly was marked by its outstanding water quality.

TABLE 5. Summary of Trophic State Model Results for Silver Lake Simulations

Silver Lake Trophic State Models					
Model		**Current**	**Current with Groundwater Recharge**	**No Diversion Inputs**	**No Diversion Inputs with Groundwater Recharge**
Vollenweider	1975	0.027	0.024	0.023	0.021
Larson and Mercier	1975	0.032	0.028	0.029	0.026
Jones and Bachman	1976	0.035	0.028	0.033	0.029
Kirchner and Dillon	1976	0.028	0.023	0.026	0.023
Average		0.031	0.026	0.028	0.025

Model simulations were then used to evaluate the effects of fundamental water operation change in the system. The most dramatic change would be to halt diversions into Silver Lake from Monponsett Pond and Furnace Pond. Ceasing diversions has two main effects: reduction of hydrologic inputs to Silver Lake; and, decrease of pollutant loads.

Ending diversions was evaluated under the two hydrologic scenarios described above with calculated net groundwater influx and the substituted groundwater recharge. In both cases, there was a slight reduction in predicted TP concentration for Silver Lake with a nearly 9% decrease in the standard hydrologic condition and about a 4% drop with the substituted groundwater recharge value. Interestingly, the Jones and Bachman model predicted an increased P concentration for the groundwater recharge hydrology when ceasing diversions. In general, reducing the diversions to Silver Lake are expected to render a positive impact on the trophic state with a decrease in primary production, but the magnitude of the reductions predicted by the remaining models was relatively minor as shown by the TP reduction that ranged between 4 and 9%.

Furnace Pond

For Furnace Pond the models were run for just the current hydrologic and pollutant budgets. Halting discharge from Furnace Pond would not change the pollutant or hydrologic budget; the only difference in hydrologic budget would be that formerly diverted water would instead be discharged through Herring Brook and while beneficial for the stream would have no effect on the trophic status of the lake. We assumed for the model that Furnace Pond and Oldham Pond represent a single unit. The predicted average TP concentration for Furnace Pond was 0.048 mg/L; matching nearly exactly the measured concentration of 0.047 mg/L (Table 4). It is worth noting that agreement among the models was relatively poor with the predicted concentrations ranging from 0.028 mg/L to 0.068 mg/L (Table 6). This finding highlights the differences in the models as mentioned above. Despite the wide range of predicted P concentrations, each model indicated the Furnace Pond system to be eutrophic.

TABLE 6. Summary of Trophic State Model Results for Furnace Pond Current Condition Simulations

Furnace Pond Trophic State Models		
Model		**Current**
Vollenweider	1975	0.028
Larson and Mercier	1975	0.068
Jones and Bachman	1976	0.065
Kirchner and Dillon	1976	0.030
	Average	0.048

Monponsett Pond

Monponsett Pond is a complex system due to a number of factors including the linking of two discrete basin units (East and West); the transfer of water between those basins; and, the export of water to Silver Lake. Monponsett Pond at this point essentially has two primary surficial outflows as a result of operation of the Silver Lake diversion from the east basin. Seasonally and at times simultaneously, water spills over the dam in the northwest to Stump Brook as well as via the diversion to Silver Lake. Hydrologic manipulation has a substantial impact on the inter-basin transfer and flow dynamics in the pond, which affects not only hydrology through diversion to Silver Lake and a loss of discharge to Stump Brook, but in the trophic state as well.

Because of its complexities, Monponsett Pond was simulated according to several scenarios (Table 7). The current trophic state was modeled in the east basin, the west basin, and for the entire system. Under the current regime approximately 70% of the entire outflow is routed through the diversion in the east basin; as a result a significant portion of the inflow in the west basin (around 40%), that historically exhibits poorer water quality compared to east basin because of higher pollutant loading, is diverted into the east basin. There also is a seasonal component to this exchange and for the most part transfer is halted from June through October by regulatory edict, except on occasions when stakeholders petition BWS to divert water to Silver Lake for flood control purposes. Modeling the entire watershed was relatively straightforward and the average predicted P concentration was 0.093 mg/L or 91% of the observed values (Table 4). Note that we removed one outlier in the observed P values (1.045 mg/L, measured in the west basin). This data point was discarded from the TP average as an extremely high value more consistent with wastewater streams. It was noted in correspondence between Lycott Environmental Inc., the lake management consultant for Monponsett Pond, and the MA Division of Fisheries and Wildlife that, "total phosphorus concentrations have varied greatly over the years".

TABLE 7. Summary of Trophic State Model Results for Monponsett Pond Simulations

Monponsett Lake Trophic State Models							
		East		West		Total	
Model		Current	No Diversion	Current	No Diversion	Current	Dam Crest Lower
Vollenweider	1975	0.075	0.057	0.082	0.090	0.064	0.070
Larson and Mercier	1975	0.130	0.111	0.202	0.142	0.127	0.135
Jones and Bachman	1976	0.116	0.100	0.196	0.126	0.117	0.122
Kirchner and Dillon	1976	0.069	0.055	0.089	0.078	0.063	0.067
	Average	0.097	0.081	0.142	0.109	0.093	0.098

Modeling the individual basins was complicated at current conditions because of the flow patterns induced by water management practice. To separate the basins for modeling purposes, Princeton Hydro apportioned both hydrologic and pollutant load according to discharge through the system. For the east basin this meant including the entire P load generated in its watershed, 71% of hydrologic input which matches the percentage of water passed through the diversion when expressed as percentage of total output minus evaporative loss (or the total of discharge to Stump Brook and diversion to Silver Lake), as well as the portion of nutrient loading to the west basin that otherwise would be transferred to the east basin.

The west basin was simpler than the east basin and included 29% of the hydrologic inputs plus the entire P load generated in the west basin subwatershed. Since all the models are based on annualized hydrologic and loading functions no effort was made to account for seasonality. The average predicted P concentration in the west basin is 0.142 mg/L; an extremely high value and indicative of a hyper-eutrophic system. The average predicted value matched closely to the observed average P concentration of 0.134 mg/L. Despite the agreement, the range of predictions was quite large from a minimum of 0.082 up to 0.202 mg/L; a pattern also noted for Furnace Pond. The predicted P concentration in the east basin was 0.097 mg/L, which is approximately three-fold greater than empirical measurements. Clearly, the model agreement is very poor and as with the west basin the models display a considerable range from a minimum of 0.069 mg/L up to a maximum of 0.130 mg/L.

The inability to model seasonal effects likely contributes to some of the disparity. With the exception of a single point, all water quality data were collected during summer months; corresponding to a season when typically there is no diversion from the east basin. Lacking diversion to Silver Lake, there is generally prevailing westward flow out of the east basin and into the west, whereas the models assume delivery/mixing of nutrient-enriched water from the west basin into the east basin. Moreover, data collection timing has coincided with the seasonal period when nutrient concentrations potentially exhibit their lowest annual level owing to reduced summer hydrologic inputs. Accurately characterizing flow patterns between the basins also remains difficult. Despite the poor calibration results of the models for the east basin, both empirical data and modeled predictions show high nutrient concentrations that are entirely consistent with a eutrophic lake.

One potential management option is to cease diverting water to Silver Lake. This was modeled to evaluate the potential trophic effects of such action. While stopping the diversion of water will have no impact on the overall hydrologic or pollutant budget of the lake, the trophic effects and flow dynamics could be considerable. If the diversion was operationally discontinued the east basin would maintain constant westward flow throughout the year. The model inputs for the east basin would therefore include the pollutant load developed in the east basin watershed and a portion of the hydrologic inputs roughly equivalent to catchment area of the east basin relative to the entire watershed. The west basin budget terms would include the entirety of the hydrologic inputs and the entirety of the pollutant load because all flow through the system would eventually be expressed through the west basin and discharged into Stump Brook.

The above-described scenario can be considered a historical evaluation of the system as this simulation scheme matches the historic flow patterns of the lake prior to diversion to Silver Lake. In the west basin, the predicted P concentration is expected to fall to 0.109 mg/L or by approximately ¼ of the current modeled values. The Vollenweider model predicted an increase in trophic state under such a scenario, but the other models all show substantial declines. In the east basin, the P concentration is predicted at 0.081 mg/L; a 17% decrease of the modeled current conditions. The model outputs for the east basin remain troublingly high, but as a planning tool the magnitude of the reductions is considered valid. Unfortunately, despite predictions of decreased nutrient concentrations and a reduction of primary productivity, both basins will remain eutrophic systems and continue to be impacted by water quality impairments. While the severity and duration of the impacts is likely to decrease, water quality conditions will likely remain problematic. As touched on in the pollutant load section, pollutant loading as a result of land use in the catchments simply remains very high and will continue to impact water quality.

One final management alternative was explored: reducing the dam crest elevation to its original 51 feet. This is another management scheme, like stopping water withdrawals that will have little impact on total nutrient loading or hydrology. Instead, lowering dam height explores a change in hydraulics within the system, namely increased flushing rate due to a decreased lake volume as well as reduced average depth. Under this scenario predicted P concentration is expected to increase approximately 6% to a concentration of 0.098 mg/L. While these models are based on regression analyses rather than deterministic approach, the decrease in mean depth is probably most responsible for a predicted increase in trophic state as the biologically-active photic zone of the lake will increase relative to total lake volume resulting in a net gain in system productivity.

5.3 Trophic State Modeling Summary

The trophic models provide some interesting data and allow an exploration of potential management options for the BWS system. Several key findings of these models are worth repeating. First, Monponsett Pond and Furnace Pond are both eutrophic, while the west basin of Monponsett Pond can be considered hyper-eutrophic. Silver Lake is likely mesotrophic, but bordering on eutrophic status as confirmed by water quality testing and supported by model results that indicate greater than 30% of the P load is derived from water diverted to the system.

Each lake and sub-basin routinely exceeds the USEPA nutrient guidance values. One major management alternative, stopping diversion of water to Silver Lake, will have a variable trophic effect throughout the system. In Silver Lake, modest improvement in water quality and reduction in nutrient concentrations are expected. In Monponsett Pond, improved water quality would likely be significant, yet due to continuing P loading issues unrelated to BWS operations, water quality impairments due to algae blooms and associated impacts of high primary production would remain in place. At Furnace Pond, there would be no expected trophic response.

6.0 DISCUSSION

Princeton Hydro examined an abundance of information regarding the macro-scale characteristics associated with the BWS system. Our review and analyses emphasized hydrologic and nutrient pollutant modeling of the individual water bodies that comprise the primary water sources. In this section, our objective is to evaluate the BWS system in the context of the overall natural resource regulatory framework as well as the impacts that current water management practices exert on the ecosystem, including the numerous ecosystem services that humans rely upon.

6.1 Regulatory Framework

When the state legislature initially granted Brockton rights to divert water from Silver Lake in 1899, few rules governed natural resources management. The paradigm in the late 19th century effectively supported resource exploitation by economically and politically powerful entities and the 1899 Chapter 356 Act largely was consistent with the mindset of the time. Yet while Act 356 authorized Brockton to use Silver Lake as its primary water source, its authors also included language that stipulated the preservation and protection of Silver Lake's water quality. Moreover, in 1899 the legislature also conferred decisions regarding water quality in Silver Lake to a state oversight body; i.e., the Board of Health[9].

Given the age of Act 356 and the emphasis placed by BWS on its "right" to divert water from Silver Lake, obtaining a modern legal context of Act 356 is warranted. In particular, Act 356 granted use of Silver Lake as a BWS source; however, water use was predicated on the maintenance of "lake purity" as well as oversight by a knowledgeable entity with decision-making authority. Subsequent legislative actions regarding BWS were mainly adopted in response to crisis circumstances and as such, included language that reflected the perspective that crisis management warranted "emergency declarations". But *emergency declaration* is terminology that implies to us actions that are temporary, finite, and applicable as interim measures used only until permanent solutions were developed. Moreover, the 1995 ACO stipulated that Brockton submit a CWMP that contained, as a core provision, ways by which BWS will optimize the use of water supplies in manners that minimize environmental impacts.

Beginning with the Water Management Act permit process in the early 1990s, the desalination plant located in Dighton, Massachusetts known initially as Bluestone, but now called Aquaria, was embarked upon primarily as a means to off-set BWS's reliance on the Silver Lake source area. The Dighton plant became active in 2008 and as of this report date, the Aquaria desalination plant is capable of supplying approximately 3 MGD of treated water to BWS, yet BWS purchases only enough water from Aquaria (~0.3 MGD) to ensure that emergency supplies are ready if needed.

As of this report date, MADEP also has not approved the draft CWMP submitted by BWS. Furthermore, in its response to MADEP reviewer comments regarding how BWS will manage water sources to minimize environmental impacts, BWS emphasized that the Silver Lake water supplies are less expensive

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[9] In the modern era in Massachusetts, the phrase *Board of Health* typically refers to a local municipal entity; whereas the State equivalent entity is the *Department of Public Health*.

than the alternative source available from Aquaria. Furthermore, BWS stated that Aquaria water would only be used to supplement water supplies beyond its registered/permitted allocation limits.

Throughout the second half of the 20th century, multiple state and federal natural resource management regulations were enacted, re-enacted, revised, and updated according to improvements in scientific understanding that many human societal needs depend on the services afforded by well-functioning ecological systems.

The current paradigm regarding natural resource management regulations, particularly with respect to water, holds that sustainability is a necessary and primary objective. At the essence of sustainability is the premise that resources be available to all legitimate users including the natural ecological communities. And for water, an over-arching factor in terms of sustainability is that water be available according to its natural flow regime. Natural flow regime supports the biological communities that evolved in response to multiple dynamic conditions. In many managed settings, including the BWS system, water manipulations disrupt and even corrupt natural flow regime, diminish water quality, and thereby impair biological communities with impacts to human society as well.

The state SWMI framework is intended to prevent unsustainable water management practices by examining and apportioning water allocation according to a watershed-scale estimate of sustainability. Despite an evolution in scientific understanding about the societal benefits, some argue imperative, for sustainability and the integrated framework of state and federal rules that govern natural resource management, the BWS system continues to operate in an unsustainable fashion. Moreover, but for certain specific exemptions "grandfathered" by its long-term tenure (e.g., Inter-basin Transfer Act, Water Management Act), the BWS system operates in manners that contradict a variety of state and federal rules.

The federal Clean Water Act (CWA) mandates that the states maintain a monitoring and assessment program for surface and groundwater to protect aquatic resources and attendant demands. In part, this mandate is accomplished through the development of the Massachusetts Surface Water Quality Standards (SWQS, 314 CMR 4.00) that: (i) designates the most sensitive uses of waterbodies throughout the Commonwealth for the enhancement, maintenance, and protection of the resource; (ii) prescribes water minimum water quality criteria; and (iii) develops the regulations to achieve the designated uses and maintain existing water quality.

The SWQS offer several anti-degradation provisions. Existing uses and the level of water quality necessary to protect the use shall be maintained and protected. High Quality (HQ) waters, those designated waters with assessed quality above certain minima or waters of special quality are granted additional protection to maintain existing levels of quality and requires MADEP authorization to modify or increase discharges. Outstanding Resource waters, including Class A Public Water Supplies, are designated based on outstanding socio-economic, recreational, ecological, and aesthetic values and shall be protected and maintained.

Class A waters are designated as sources of public water supply, including their tributaries, and generally recognized for their excellent water quality and supporting fish, other aquatic life, and wildlife for reproduction, migration, growth, and other critical functions. These waters are subject to the Outstanding Resource Waters anti-degradation provisions. Class B waters are designated as habitat for fish, other aquatic life and wildlife for reproduction, migration, growth, and other critical functions, and for primary and secondary contact recreation. Such water bodies may be used for public water supply with treatment, and support irrigation, agricultural, and industrial use. Class C waters are similar to Class B waters and largely support the same uses, but are not suitable for water supply or for primary recreation. Water quality criteria are somewhat reduced in these systems. None of the BWS source waters are designated as Class C waters.

Most of the waters in the system are designated as Class A Public Water Supply, which befits their primary use and is assigned to tributaries of the system. Three of the water bodies, the natural outlets of the three main reservoirs, are classified as Class B waters. These are also classified as HQ waters, with the exception of Herring Brook which is identified as an Outstanding Water Resource according to the anti-degradation provisions.

A second provision of the CWA requires formal monitoring of aquatic resources and reporting of the findings in the Integrated Report, which combines the Section 303(d) and 305(b) lists. Perhaps the most significant use is the identification of impaired waters; i.e., water bodies that do not meet designated uses or otherwise contravene the water quality standards and anti-degradation provisions. One of the outcomes of assessing a water body as impaired is that it can, depending on the nature of the documented impairment, trigger the development of a TMDL per 40 CFR 130.7. A TMDL is a load calculation and set of management practices to affect a reduction in pollutant load given the hydrology, morphometry, and other pertinent factors to bring a water body into compliance with the water quality standards or designated uses.

With the exception of the TMDL already completed for the east basin of Monponsett Pond (EPA TMDL #33880), most of the listings are due to a ubiquitous pattern of impairment throughout New England and the Mid-Atlantic characterized by cultural eutrophication related to excessive nutrient loading, the construction of dams and alterations to hydrology, and colonization of invasive macrophytes, all processes that are frequently interrelated. It should be noted that the TMDL completed for the east basin of Monponsett Pond was part of a regional TMDL developed to address atmospheric Mercury loading, most of which originates internationally. In any case, all three of the major water supply basin systems (Silver Lake, Monponsett Pond (east and west basins), and Furnace Pond/Oldham Pond) covered by this project are known to be impaired both by pollutants and non-pollutants and all of these systems or their respective receiving water bodies require a TMDL. The TMDL for the west basin of Monponsett Pond is being prepared presently. At a minimum, the impairments in water quality and the inability to meet designated uses for the water bodies represent a significant threat to the water supply for the BWS and water management must work towards meeting designated uses and water quality criteria.

6.2 Deviation from Natural Flow Regime

The BWS system is a substantial alteration of the natural flow regime that involves multiple watersheds.

It is rather easy to surmise that the lack of discharge to Jones River is a simple consequence of the diversion of over 3,400 MG per year and while that is true at a base level a more detailed look at the hydrology of the system shows that the seasonal aspect of water movements in the basin are chiefly responsible for this effect. From June through September Silver Lake loses well over 100 MGM of storage as a consequence of continuous withdrawal from the lake; lack of input in the form of diversions from Monponsett Pond and Furnace Pond; and increased ET demand. The loss of storage is manifested primarily in decreased lake stage and as such the lake stage is simply too low to initiate or sustain discharge to the Jones River. It must be emphasized that Silver Lake is major a headwater element for Jones River and the lack of connection between the lake and its outlet is a significant alteration of natural flow.

Even the period from October through February when Silver Lake storage is increasing due in large measure to supplemental inputs from outside the natural watershed, lake stage still remains well below the Forge Pond dam crest elevation and thus there is no discharge to the river.

The BWS demand on water resources however extends well beyond the limits of Silver Lake, its watershed, and Jones River and instead the demands and related impacts are transmuted by the diversions to impact Monponsett Pond and Furnace Pond. Monponsett Pond in particular is heavily utilized to subsidize the water demand for Silver Lake. Each year 2,300 MG are diverted to Silver Lake or ~60% of the total annual inputs of the Monponsett Pond watershed. This is a proportionally high utilization rate of the overall watershed budget, but considerably less than that of Silver Lake at 84%. The Monponsett Pond rate of use does permit some maintenance of natural hydrologic functions including relatively stable lake stage and discharge to Stump Brook. While Stump Brook is modeled to have discharge for most of the year, such discharge (controlled through a fish ladder and with periodic flow across a broad weir) is much-reduced as a consequence of BWS' diversions out of the natural watershed.

Indeed, the ~60% of annual hydrologic load that is shunted to Silver Lake due to BWS management practice would otherwise be expressed as stream discharge and increase the current annual flow to Stump Brook by approximately 345%. Considered differently, stream flow in Stump Brook is approximately 1/3 of its natural potential. As with the Jones River, diminished flow status represents a significant loss in aquatic habitat functions in Stump Brook.

Furnace Pond is much less heavily utilized than Monponsett Pond in both absolute and relative terms for supplying water to Silver Lake. Only about 245 MG are diverted from Furnace Pond annually; a volume equivalent to approximately 10% of the diversion from Monponsett Pond into Silver Lake. Withdrawals from Furnace Pond account for about 18% of the total inputs to Silver Lake. As a result, a much higher percentage of water in the system is discharged through Herring Brook. When examined on a unit area basis, discharge in Furnace Pond is greater than twice that of Monponsett Pond, suggesting that the outflow from Furnace Pond more closely approximates the natural flow regime than other components of the BWS system.

6.3 Non-Sustainability

A global perspective on sustainability of the BWS system was provided by the water budgets. In particular is the comparison of watershed precipitation versus withdrawals from Silver Lake. Watershed precipitation can be thought of as the total annual water naturally available in the watershed. Current production of treated water from Silver Lake by BWS is equivalent to 99.2% of average annual precipitation in the Silver Lake watershed; in effect, leaving just 0.8% for all other functions, such as discharge to the Jones River and ET.

A more realistic estimate of water that is actually available accounts for natural hydrologic loss through ET in the watershed is to use the sum of groundwater recharge and direct precipitation. Groundwater recharge is calculated simply as recommended in the USGS studies by subtracting PET from precipitation on a monthly scale; where ET exceeds precipitation recharge is considered nil. Using these more appropriate metrics, finished water production is ~1,200 MG greater than the sum of direct precipitation and groundwater recharge. In other words, the BWS system extracts more than 150% of the naturally available water in the watershed.

This stark over-allocation of Silver Lake's natural hydrologic capacity to support BWS' water demand forms the essence of why so much water must be diverted from Monponsett Pond and Furnace Pond.

In Silver Lake, these obvious deficits are offset/subsidized by diverting water from adjacent watersheds; diversions that supply more than 2,600 MG annually to Silver Lake. Again, even with this broad scale of supplemental inputs, there is insufficient water in the Silver Lake system to maintain other hydrologic functions, particularly discharge and connection to the upper reach of Jones River. It is well documented that the upper reaches of Jones River are dry during the summer months and often much longer. In complete contrast to the expected natural hydroperiod of this region, flows in the upper Jones River reach tend to be ephemeral or perhaps intermittent before becoming perennial at the confluence of several large tributaries in excess of one mile downstream of the Forge Pond/Silver Lake dam. The ecological consequences of an altered hydrologic regime in the Jones River include compromises for migratory species that ascend and descend Jones River to Silver Lake, as well as complete loss of aquatic ecosystem services in the upper reaches of the river.

In the context of the regional hydrogeologic setting, Silver Lake and its natural outlet Jones River can be expected to have maintained tangible hydrologic connectivity in the past. The historical topographic maps generated in the late 1800s speak to this point in that extensive wetland features and "blue line streams" were depicted at the outlets of Silver Lake, Monponsett Pond, and Furnace Pond.

6.4 Pollutant Loading and Trophic Status Considerations

The primary water source water bodies in the BWS system range from mesotrophic to hyper-eutrophic at current conditions. Pollutant loading analyses suggest different management pathways for each of the watersheds in an effort to control nutrient loading. By far the simplest lake to control nutrient loading for is Silver Lake where, from a mechanistic perspective, a 30% reduction could be achieved simply by halting the diversion of water from nutrient-enriched Monponsett and Furnace Ponds.

Management of nutrient loads in the other lake basins is somewhat more difficult to achieve. Certainly septic loading, which accounts for nearly 15% of the P budget in Furnace Pond, seems to be a sensible target area. In Monponsett Pond, options to affect nutrient reduction are more limited. Storm water management and other NPS mitigation strategies may prove largely ineffective until cranberry operations are curtailed in the watershed. This statement agrees with the general assessment by the consultant for Monponsett Pond. The overwhelming nutrient load that is delivered to the Monponsett Ponds is unfortunately best attacked through in-lake management alternatives such as the use of alum for nutrient control or the installation of aeration/destratification systems. While the trophic state analysis shows that the manipulation of water in Monponsett Pond contributes to decreased water quality in the system, ultimately it has been the development practices and land uses of the watershed that have contributed to high P loading.

6.5 Aquatic Life Considerations

The impacts of reduced stream flow to the outlets of each lake in the BWS system already affect fish passage and other aquatic functions.

As explored in the water quality designations, all of the waterways and water bodies in the project area are designated as either Class A or Class B waters. As such, these waters are subject to surface water quality standards and anti-degradation provisions. While these are of utmost importance in the management of water bodies for water supply, the designated uses of both of these classes includes maintaining the water bodies and hydraulically-connected systems as habitat, especially for aquatic organisms. Maintaining habitat, as was discussed in the context of natural flow regime, is primarily dependent on maintaining sufficient water quality including dissolved oxygen concentrations, nutrients concentrations, and other factors, as well as maintaining the hydrology/hydraulics of a system including storage, flow, and discharge.

Two broad categories of habitat maintenance; water quality and quantity, are interrelated as demonstrated in the trophic state modeling section. An exploration of life history constraints is provided below for three broad taxa in the project setting in the context of lake management currently and as projected. The taxa include: fish, mussels, and phytoplankton/algae.

Fish

Habitat impacts to diadromous fish are probably the best-studied biological component in the BWS system and efforts to restore migratory runs have been a long-standing goal of stakeholders as well as a regulatory compliance issue. Diadromous fish refers to a broad functional group of species that exhibit migratory movements for reproductive purposes between freshwater and saltwater. In the project watersheds, the major species of concern include: two anadromous river herring of the genus *Alosa* (blueback herring *A. pseudoharengus* and alewife *A. aestivalis*) which migrate from the estuary into river systems to spawn in the spring followed by the downstream passage of juveniles in the autumn; and the catadromous American eel (*Anguilla rostrata*), which enters freshwaters as larval/juvenile forms and resides for a period of several years before sexually mature adults descend the river systems to spawn in the Sargasso Sea in the sub-tropical Atlantic basin.

In the BWS system lakes, there are two main constraints that limit diadromous fish reproductive success: (i) physical barriers to migration including various dams regulating lake stage; and, (ii) hydrological barriers including a physical lack of discharge/connectivity with a seasonal timing component.

In the current configuration of the system, migrating species are capable of passing into and out of Furnace Pond via the fishway at the dam on Gorham Mill Pond linking Herring Brook and Furnace Pond. In Monponsett Pond there is no known current run of migratory fishes. While the dam at Stump Brook does have an operational fishway, downstream barriers prevent any passage to the face of the dam. Silver Lake similarly has no runs of migratory fish for a variety of reasons. Until recently barriers downstream prevented migratory runs from reaching Silver Lake, but with the recent removal of the Wapping Road dam, fish can now pass freely up the Jones River by traversing the fish ladder at the Elm Street dam, passing through the re-naturalized channel at Wapping Road. However, the Forge Pond dam linking the Jones River and Silver Lake remains impassable.

A thorough and detailed analysis of improving passage was published in the *Forge Pond Dam Fish Passage Improvement Feasibility Study and Preliminary Design* draft report (Gomez and Sullivan, 2013) which identified several fishway alternatives and the specific stream hydraulics necessary to pass fish. While designing and installing a fishway will be relatively straightforward, the major constraint in the system is discharge of water to Jones River and related lake stage. Spring passage is feasible under current management of the lake and Silver Lake discharges to the Jones River from March through May. However, the outbound migration of juvenile river herring in the autumn is not possible under the current management scheme. In fact, the downstream period of passage actually coincides with the period of lowest lake stage when, on average, Silver Lake is around three feet lower than the spillway crest. Successful fall passage would require major alterations in water diversions in an effort to maintain the lake at higher stage to the point where the lake would spill. This may be possible if some of the withdrawals of Silver Lake are offset by sources elsewhere.

While no fish are migrating into Silver Lake from Jones River, the *Silver Lake Overview Report* (HMA, 2006) notes the possibility of fish entrainment in the diversion from Furnace Pond and "as alewife are present in Silver Lake and the Furnace Pond diversion is the only possible source of the fish." Certainly if alewife, particularly juveniles, are leaving Silver Lake via the Jones River it is not during the crucial fall period, but rather during the spring. This obviously has a direct impact on the recruitment success of the Furnace Pond river herring fishery, but the magnitude is unknown. In any case, the twin threats of barriers and insufficient discharge have effectively eliminated the diadromous fishery in both Monponsett Pond and Silver Lake, but with efforts to improve river passage in general throughout the United States and specifically in the Jones River with the removal of the Wapping Road dam, issues of passage will need to be addressed in order to complete full restoration of the river for diadromous fish.

As noted in the *River Herring Spawning and Nursery Habitat Assessment* (Chase et al., 2013), the water quality condition of Silver Lake "would support river herring spawning and nursery habitat requirements"; establishing successful recruitment in Silver Lake would be possible if migratory pathways were re-opened.

Freshwater Mussels

FIGURE 16. 2002 Aerial image that depicts severe drawdown in Silver Lake in the vicinity of Forge Pond/outlet to Jones River.

Another important taxa in the BWS system are the freshwater mussels. Mussels are filter feeding bivalves that can help maintain water quality through the removal of phytoplankton. Mussel populations have been extremely impacted throughout much of the country for a number of reasons including degradation of substrate quality, physical loss of habitat, pollution, low dissolved oxygen concentrations, barriers to host species migration, alteration to flow regime, and overharvest among others. Mussels are of particular interest in Monponsett Pond and Silver Lake because there are confirmed populations of tidewater mucket (*Leptodea ochracea*) and eastern pondmussel (*Ligumia nasuta*), both listed as Species of Special Concern. The mussel fauna of Furnace Pond is not described.

Tidewater mucket and eastern pondmussel are under some degree of risk in the BWS system. In Silver Lake the major cause for concern and one that has been documented on several occasions, including in 1997 and 2002 (Figure 16), is the loss of mussels due to stranding caused by excessive drawdown of the lake. The *Silver Lake and Jones River Watershed Study* (Teal, 2000) noted that, "water level manipulations may potentially have significant impacts upon the freshwater mussel populations in the long term". BWS has addressed this concern in the *Comprehensive Water Management Plan* partially by attempting to limit the operating band and minimizing lake drawdown (CDM, 2009). However, even small level manipulations could continue to have an impact; the eastern pondmussel fact sheet prepared by the South Carolina DNR notes that the shallows it inhabits "may make it especially sensitive to sudden drops in water levels".

In Monponsett Pond the threat to populations is somewhat different and is related to eutrophication of the system resulting in poor water quality. The exact links between eutrophication and mussel populations is not well studied, but it is demonstrated that native unionid mussels accumulate cyanotoxins produced by blue-green algae in their tissues during bloom events, which has been a persistent problem in Monponsett Pond. Furthermore, physiological adaptations to excrete or transform the toxins and other pollutants is less for unionids relative to invasive species like the zebra mussel (Burmester et al., 2011).

One of the few management options to combat cultural eutrophication and nuisance cyanobacteria blooms in Monponsett Pond is the application of aluminum sulfate or alum to bind P. There is some concern that the application of alum could potentially harm mussel populations in the lake either through direct toxicity or by smothering by substrate with alum/biological flocculant. Lycott Environmental, in their application submitted to the Division of Fisheries and Wildlife, pointed to studies showing the stress to mussels related to alum applications was temporary and that aluminum was quickly cycled through the tissues. In addition, Lycott also developed a comprehensive monitoring criteria to protect mussels during the application of alum in the *Habitat Management Plan for Phosphorus Inactivation in the Western Basin of Monponsett Pond* (Lycott, 2012) scheduled for the summer of 2013.

While the risks to mussels posed by management actions in these systems has been minimized, there is one threat that remains unresolved. Native unionid mussels produce a larval form called glochidia that require attachment to the gills of fish hosts which amongst other functions help to distribute populations. In New Jersey, the host of the tidewater mucket is unknown, but “it is thought to be anadromous” (Bowers-Altman, 2012). Because anadromous species are extirpated from Monponsett Pond and are denied general access to Silver Lake, the lack of an anadromous fish host could impact these species.

Phytoplankton

The last major taxa to be investigated is phytoplankton included algae and cyanobacteria or blue-green algae. Unlike the other taxa which are threatened with direct population loss and reduced recruitment or reproductive success, the phytoplankton have responded by an increase in biomass as a result of the change in trophic state dynamics and increased nutrient concentrations. These interactions and the management practices that contribute to them have been well documented in the trophic state models and the high nutrient concentrations in exceedance of EPA regional nutrient guidance are confirmed by available water quality sampling data.

One of the impacts of high nutrient concentrations is a shift in phytoplankton community composition towards the cyanophytes. Cyanobacteria enjoy a competitive advantage in P-enriched environments for several reasons. One of the main reasons is that blue-green algae can fix gaseous N; this is important because all living organisms require nutrients in certain ratios and in the case of high P environments, the ability to fix N means that these algae can effectively utilize P at a much higher rate. Another advantage is that unlike other phytoplankton cyanobacteria can utilize organic forms of P that are otherwise unavailable to other autotrophs or photosynthetic organisms.

In addition to their improved nutrient assimilation capacities, blue-greens are largely unpalatable to zooplankton which normally graze other algae and thus control densities. One of the reasons that blue-greens are not effectively grazed is that they produce a series of toxins, known collectively as cyanotoxins, which include hepatotoxins (blood agents) and neurotoxins (nerve agents). Blue-green algae and cyanotoxins disrupt the entirety of the food web and can cause crashes in zooplankton populations, impact mussels, and in high enough concentrations can prove lethal to fish and other wildlife. There have even been documented cases of cyanotoxin induced death of livestock that have been watered from farm ponds during algae blooms. Because of their numerous competitive advantages, blue-green algae are more likely to reach and maintain bloom densities.

A review of the phytoplankton from the summer of 2009 in Monponsett Pond (Northeast Laboratories, 2009) showed the cyanobacteria to be a consistent and often major component of the plankton community throughout the summer, often reaching bloom densities. This factor has caused closures of public bathing areas to avoid public health effects. Despite the direct risks to human health, some of the secondary impacts of blue-green algae may in fact cause more ecological damage. One of the problems associated with blue-green algae blooms is wild swings in dissolved oxygen concentrations. During the day dissolved oxygen spikes as the algae are actively photosynthesizing, but at night the algae continue to respire and thus deplete oxygen. Depletion of oxygen is in fact more severe when the bloom senesces generating a large mass of organic material. Bacterial decomposition of the dead algal cells can therefore cause hypoxia or anoxia, which can cause fish kills or contribute to internal nutrient loading.

There was suspicion among some lakeside residents as memorialized in an email chain that an October 2011 fish kill at Monponsett Pond was linked to an algae bloom. Other effects of severe blooms include an impact to aesthetics and of course a major loss of primary and secondary contact recreation.

A final impact of blue-green density to consider is the interbasin transfer from Monponsett Pond to Silver Lake. While the concentration of phosphorus is much less in Silver Lake relative to Monponsett Pond and thus not capable of supporting the extremely high density blooms that are encountered in Monponsett Pond, the pulse of viable blue-greens cells to Silver Lake probably affects the plankton composition of that lake as well as enabling a net influx of cyanotoxins to a public water supply.

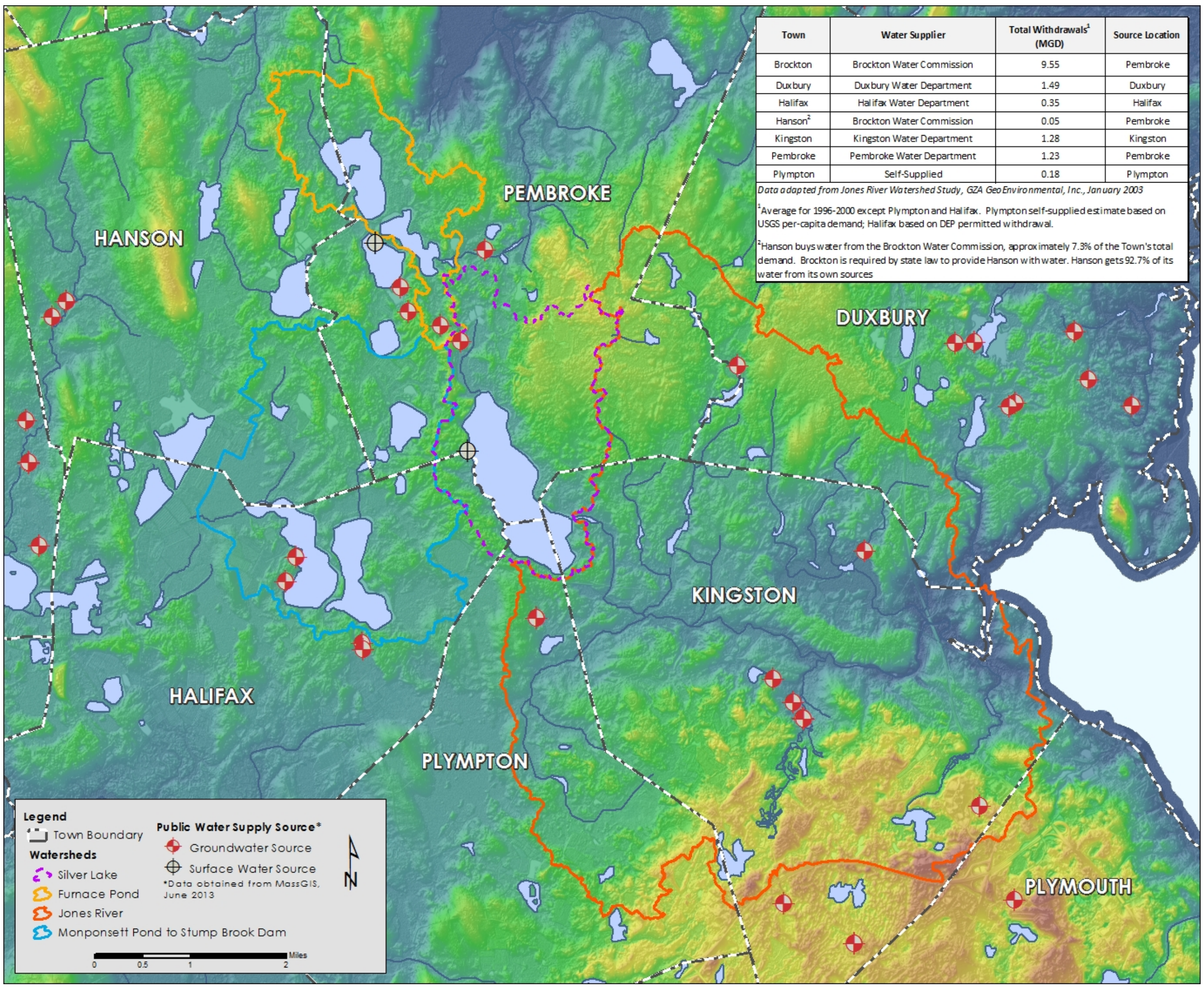
6.6 Projected Demand Increases

According to the Comprehensive Water Management Plan (CDM, 2009) issued by the City of Brockton, water use demands are expected to begin rising with projected increases in population and industrial activity, following years of declines. Any additional withdrawal from the Silver Lake system has a cascading effect and additional take from Silver Lake will require offsets from Monponsett Pond and Furnace Pond, which at least in the short-term result in decreased discharge to the stream systems as well as further strain efforts to manage nutrient loading.

Increases in water demand will have a serious impact on water supply. Already Silver Lake discharges to Jones River for only three months out of the year and both Monponsett Pond and Furnace Pond discharge to their respective outlet rivers at reduced rates, which can be expected to worsen with increasing delivery of water by BWS out of Silver Lake.

A somewhat different consideration lies with respect to climate change predictions. Princeton Hydro conducted an analysis of available climate data for the region and one trend emerged that could have impact on regional water supply and availability. Our calculations indicate that growing season total ET in the region increased approximately 15% during the 20th century. The implication of increased ET with respect to the hydrologic budget of the region is to increase the output portion of the water balance equation. We did not note an increase in input factors, especially precipitation for the same period of observation. Note that we calculated PET and *potential* ET will not be realized unless there is adequate moisture source available in the system; therefore, actual ET is less than PET. Still, if this apparent trend manifests, then additional constraint will, or already is, being placed on the availability of water resources in the region.

Additionally, the individual watersheds that BWS uses as its primary water source each support various other human populations as well as ecological communities. For example, Figure 17 below shows the locations of municipal water supply wells in the vicinity of the BWS source area and in addition to BWS, the Jones River watershed provides approximately 1.7 MGD to other public water supply entities.



Town	Water Supplier	Total Withdrawals[1] (MGD)	Source Location
Brockton	Brockton Water Commission	9.55	Pembroke
Duxbury	Duxbury Water Department	1.49	Duxbury
Halifax	Halifax Water Department	0.35	Halifax
Hanson[2]	Brockton Water Commission	0.05	Pembroke
Kingston	Kingston Water Department	1.28	Kingston
Pembroke	Pembroke Water Department	1.23	Pembroke
Plympton	Self-Supplied	0.18	Plympton

Data adapted from Jones River Watershed Study, GZA GeoEnvironmental, Inc., January 2003

[1]Average for 1996-2000 except Plympton and Halifax. Plympton self-supplied estimate based on USGS per-capita demand; Halifax based on DEP permitted withdrawal.

[2]Hanson buys water from the Brockton Water Commission, approximately 7.3% of the Town's total demand. Brockton is required by state law to provide Hanson with water. Hanson gets 92.7% of its water from its own sources

FIGURE 17. Locations of Public Water Supplies in the project area.

7.0 CONCEPTUAL MANAGEMENT ALTERNATIVES

Overall, our evaluation of the primary BWS sources demonstrates that existing water management practices are not sustainable. The artificial movement of water across natural watersheds results in a suite of negative consequences for ecological and human communities that inhabit the setting. The primary negative impacts of water management practice include deviation from natural stream flow regime in Jones River, Stump Brook, and Herring Brook; accelerated cultural eutrophication of Monponsett Pond and Silver Lake; and, heightened concern for the long-term integrity of sensitive environmental settings such as the Stump Brook Wildlife Sanctuary and the Burrage Pond Wildlife Management Area.

BWS has come to rely on sources of water well beyond the City's limits. Through a series of water management crises, BWS has developed a water management practice that defies natural hydrologic conditions. Furthermore, BWS rejects an alternative water source, Aquaria, that will off-set the over-reliance on the Silver Lake system by citing economic factors. Yet in rejecting Aquaria as a mitigating water supply on economic grounds, BWS does not acknowledge that its water management practices with respect to the Silver Lake source area include many costs (direct and indirect financial; as well as diminished ecosystem services) that are not borne by its customers. In the following subsections, we discuss concepts in which to manage particular aspects of the BWS system in manners that minimize or off-set of the negative effects attributable to current practice.

7.1 Nutrient Management

Management of the lakes and watersheds for general trophic state reduction and for the control of algae in particular can take several forms. While watershed-wide efforts to control pollutant loading or source control is the favored method of reducing P concentrations and the major component of the viable, long-term control of algae in system, in-lake measures are usually required in conjunction with watershed measures to effectively manage eutrophic water bodies. In-lake measures usually include treatment with copper-based algicides. While this is a viable way to control algae, there are secondary impacts including DO depletion upon cell death, enhanced nutrient cycling as a result of cell lysis which is the mode of operation of most of the algicides, a crash of zooplankton populations, or even long-term resistance to copper. Judicious use of algicides is necessary and compliance with federal and state regulations regarding the use of the products can minimize the impacts of these products. Use of alum is also a proven and effective solution to reduce nutrient concentrations or even directly strip suspended particles. The potential impacts of alum to non-target taxa can also be avoided by conducting bench tests (jar tests) to identify the appropriate dose and by conducting dosing in conjunction with monitoring to avoid deleterious; the treatment program designed by Lycott includes both of these cautions and therefore should prove effective. Another option, which is being weighed among others by Halifax, is the use of a submerged destratification/aeration system. These systems maintain lakes in a mixed state to avoid hypolimnetic anoxia which promotes internal nutrient loading. By maintaining the lakes in a mixed state they can also serve to disrupt the stable stratification that promote the formation of blooms of certain blue-greens such as *Oscillatoria.* While surface mixers can be effective in coves to induce some flow, these types of systems do nothing to treat root causes and rather function through displacement of the problem rather than true treatment.

As mentioned above, watershed controls are favored for long-term management of water bodies. There are a wide variety of measures that can be employed in watersheds as follows:

- Basic regulatory and ordinance can be effective in limiting nutrients and can include measures like implementing stream buffer protection, steep slope ordinances, erosion and sediment control plans for development activities, and enforced septic management.
- Protection of riparian buffers is extremely important as well, which may require the establishment of conservation easements or outright purchase of functional buffers or the mitigation of disturbed buffers.
- Stormwater control measures including environmental-friendly structural designs are a large component, as is maintenance of existing systems.
- Cultural practices, such as curbing fertilizer use, and the implementation of agricultural best management practices like conservation tillage, manure management, and applying only necessary fertilizers are equally important, especially in the watersheds of Monponsett Pond and Furnace Pond where agricultural pollutant loading from cranberry bogs is a major component of the pollutant budget.
- Bed and bank stabilization is also important in degraded stream systems.

Limiting or stopping the diversion of water to Silver Lake could also contribute to major improvements in water quality and a reduction in algal biomass in Monponsett Pond, as was explained in greater detail in the trophic state analysis, as well as improving flow and habitat utilization in Stump Brook. A final management measure to consider is to lower the Stump Brook dam back to the 51 feet. While the trophic state model actually predicted a slight increase in phosphorus concentration in the system, one important factor that was not included in that model was the potential reduction in septic loading. Lowering the dam is expected to result in a subtle lowering of the water table adjacent to the lake and by severing the direct hydraulic connection of the fields and leachate with the water table would probably result in decreased loading to the lake.

7.2 Hydrologic Management

Primarily, the BWS system represents an unsustainable use of water sources for use well beyond the source setting. The strain on water sources in the source areas leads to cascading impacts on water quality, ecosystem functions, and property value.

The most obvious alternative to existing practice is to apportion BWS to more and/or different sources in order to alleviate strain on Silver Lake, Monponsett Pond, Furnace Pond and their respective watersheds. The Aquaria desalination plant offers a seemingly sensible alternative source for BWS to offset as much as 50% of water currently sourced from Silver Lake.

In acknowledgement that BWS existing infrastructure is capitally invested in the Silver Lake WTP, excessive reliance on Silver Lake surface water could be negated or off-set by piping water directly from

Monponsett and/or Furnace Pond to the WTP and eliminating the detrimental mixing of low quality water from those basins with higher quality Silver Lake water. Directly feeding raw stock water into the Silver Lake WTP also would alleviate the need to shunt excess volumes into Silver Lake in order to maintain a certain storage volume/water surface level.

A somewhat related, but different approach is to develop a groundwater supply system in the vicinity of Silver Lake or that can be piped to the WTP. By using horizontally-oriented intake wells, placed low in the PCKD aquifer system, it may be possible to extract water without inducing many of the deleterious effects of surface water withdrawal. Horizontal orientation enables increased intake surface area contact with the highly productive aquifer. By increasing the overall contact area, the withdrawal rate per unit area can be lower than in a shorter, vertical well; thereby minimizing local drawdown effects.

Development/utilization of any water source alternatives to the current Silver Lake system requires new capital investment or other additional cost, but the long-term cost of unsustainable water supply management is a costly endeavor right now. In the case of BWS system; however, Brockton and its customers do not bear all of the costs.

What is the true value of water? Water is vital for all life, but also essential for disease protection, sanitation, fire suppression, economic development, and a host of other factors required by human society. The collection, treatment, and distribution of water is costly and requires on-going investment, but the unsustainable use of water may ultimately cost even more.

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9.0 APPENDIX

TABLE 8. Water budget summary.

Silver Lake Water Budget								
	Input (MGM)				Output (MGM)			
	P_D	D_{MP}	D_{FP}	GW_{NET}	Q_{JR}	ET_D	W_{SL}	ΔS_{SL}
Jan	69.93	349.94	55.36	-22.58	0.00	0.00	298.48	154.16
Feb	64.59	273.59	44.40	-3.92	0.00	0.00	264.65	114.02
Mar	75.45	391.46	48.66	-92.84	16.03	6.20	286.02	114.47
Apr	72.00	343.79	35.74	-32.15	149.30	24.98	273.60	-28.49
May	59.25	251.05	15.89	120.38	88.16	53.57	292.79	12.06
Jun	56.33	62.37	11.27	110.45	0.00	78.72	293.76	-132.06
Jul	54.09	28.17	0.00	129.91	0.00	94.57	303.05	-185.45
Aug	66.66	15.40	0.00	137.14	0.00	90.95	293.37	-165.12
Sep	66.66	20.81	0.00	121.00	0.00	58.57	274.44	-124.53
Oct	65.28	153.52	3.59	109.85	0.00	34.11	281.22	16.91
Nov	76.31	183.99	18.36	70.69	0.00	13.44	276.15	59.76
Dec	77.00	274.17	37.34	27.10	0.00	0.69	287.37	127.55
Total	803.55	2618.87		675.03	253.49	455.78	3424.91	-36.72

Monponsett Pond Water Budget							
	Input (MGM)			Output (MGM)			
	P_D	D	GW_{NET}	Q_{SB}	ET_D	W_{MP}	ΔS_{MP}
Jan	91.28	0.00	318.83	57.21	0.00	360.14	-7.24
Feb	65.24	0.00	352.49	50.80	0.47	308.11	58.35
Mar	116.46	0.00	624.19	229.53	11.32	487.22	12.58
Apr	80.74	0.00	479.85	139.75	34.16	459.13	-72.44
May	85.91	0.00	238.51	60.28	57.98	230.23	-24.07
Jun	68.41	0.00	91.19	46.98	79.39	14.34	18.90
Jul	104.02	0.00	59.88	47.48	109.20	39.81	-32.59
Aug	104.69	0.00	91.28	37.56	107.42	0.00	50.98
Sep	88.37	0.00	35.64	57.66	78.07	0.00	-11.72
Oct	131.19	0.00	102.90	72.43	47.54	51.67	62.45
Nov	72.40	0.00	122.96	74.01	24.72	138.53	-41.90
Dec	99.98	0.00	201.02	75.92	4.61	236.63	-16.16
Total	1108.71	0.00	2718.75	949.62	554.87	2325.83	-2.87

Furnace Pond and Oldham Pond Water Budget							
	Input (MGM)			Output (MGM)			
	P_D	D	GW_{NET}	Q_{HB}	ET_D	W_{FP}	ΔS_{FP}
Jan	43.34	0.00	79.12	43.39	0.00	54.96	24.11
Feb	30.97	0.00	96.31	54.53	0.22	51.49	21.04
Mar	55.29	0.00	157.20	129.31	5.37	57.62	20.17
Apr	38.33	0.00	93.37	97.86	16.22	37.98	-20.36
May	40.78	0.00	65.78	74.61	27.52	6.09	-1.67
Jun	32.48	0.00	63.34	65.31	37.69	0.13	-7.31
Jul	49.38	0.00	38.51	54.98	51.84	0.00	-18.93
Aug	49.70	0.00	55.77	46.59	51.00	0.00	7.88
Sep	41.95	0.00	32.48	50.50	37.06	0.00	-13.14
Oct	62.28	0.00	26.44	53.95	22.57	0.00	12.20
Nov	34.37	0.00	67.44	66.81	11.73	0.00	23.27
Dec	47.46	0.00	34.92	66.87	2.19	36.71	-23.38
Total	526.34	0.00	810.67	804.71	263.41	244.99	23.89

TABLE 9. Water budget model inputs.

Silver Lake Model Inputs

	Q_{JR} cfs	Precipitation inches	PET inches	Withdrawal MG
Jan	0	4.06	0	298.48
Feb	0	3.75	0	264.65
Mar	0.8	4.38	0.36	286.02
Apr	7.7	4.18	1.45	273.60
May	4.4	3.44	3.11	292.79
Jun	0	3.27	4.57	293.76
Jul	0	3.14	5.49	303.05
Aug	0	3.87	5.28	293.37
Sep	0	3.87	3.4	274.44
Oct	0	3.79	1.98	281.22
Nov	0	4.43	0.78	276.15
Dec	0	4.47	0.04	287.37
Source	GZA, 2003 Developed, observed flows	GZA, 2003 Plymouth-Kingston	GZA, 2003 Plymouth-Kingston, Thornthwaite method	BWS Spreadsheet 1997-2012

Monponsett Pond Model Inputs

	Q_{SB} cfs	Precipitation inches	PET inches	Diversion MG
Jan	2.86	4.46	0.00	360.14
Feb	2.54	3.19	0.02	308.11
Mar	11.46	5.69	0.55	487.22
Apr	6.98	3.95	1.67	459.13
May	3.01	4.20	2.83	230.23
Jun	2.34	3.34	3.88	14.34
Jul	2.37	5.08	5.34	39.81
Aug	1.87	5.12	5.25	0.00
Sep	2.88	4.32	3.81	0.00
Oct	3.62	6.41	2.32	51.67
Nov	3.69	3.54	1.21	138.53
Dec	3.79	4.89	0.23	236.63
Source	BWS Spreadsheet Used stage data and calculated flow over weir and through fishway	CLIMOD Plymouth-Kingston, 2009-2012	CLIMOD Plymouth-Kingston, Thornthwaite method, 2009-2012	BWS Spreadsheet 1997-2012

Furnace Pond Model Inputs

	Q_{HB} cfs	Precipitation inches	PET inches	Diversion MG
Jan	2.17	4.46	0.00	54.96
Feb	2.72	3.19	0.02	51.49
Mar	6.45	5.69	0.55	57.62
Apr	4.88	3.95	1.67	37.98
May	3.72	4.20	2.83	6.09
Jun	3.26	3.34	3.88	0.13
Jul	2.74	5.08	5.34	0.00
Aug	2.33	5.12	5.25	0.00
Sep	2.52	4.32	3.81	0.00
Oct	2.69	6.41	2.32	0.00
Nov	3.33	3.54	1.21	0.00
Dec	3.34	4.89	0.23	36.71
Source	BWS Spreadsheet Used stage data and calculated flow over weir and through fishway	CLIMOD Plymouth-Kingston, 2009-2012	CLIMOD Plymouth-Kingston, Thornthwaite method, 2009-2012	BWS Spreadsheet 1997-2012

TABLE 10. Discharge formulae.

Denil Fishway Calculations

$Q = C_d h_u^{1.75} b^{0.75} \sqrt{g s_o}$

	Monponsett	Furnace
C_d	0.972	0.972
h_v	0	0
c	0.4921245	0.4921245
b	1.18	1.15
g	32.174	32.174
s_o	0.2	0.2
H	(Stage/12+51.58)-51	(Stage/12+56.08)-55.5

Thin-Crested Weir Calculations

$Q = CLH^{3/2}$

	Monponsett	Furnace
C	3.3	3.3
L	68	36
H	(Stage/12+51.58)-53	(Stage/12+56.08)-57

TABLE 11a. Hypsographic data.

Silver Lake Hypsographic Data

Depth	Volume			Interval
	ft^3	yd^3	MG	MG
0	684,987,396	25,369,904	5124.06	205.52
1	657,513,437	24,352,350	4918.54	202.67
2	630,420,337	23,348,901	4715.87	198.76
3	603,850,339	22,364,827	4517.11	193.02
4	578,046,855	21,409,143	4324.09	184.29
5	553,410,286	20,496,677	4139.80	173.94
6	530,157,984	19,635,481	3965.86	161.34
7	508,590,525	18,836,686	3804.52	152.20
8	488,243,928	18,083,108	3652.32	145.65
9	468,773,480	17,361,981	3506.67	140.81
10	449,949,365	16,664,791	3365.85	652.16
15	362,768,251	13,435,861	2713.69	575.40
20	285,847,971	10,586,962	2138.29	513.41
25	217,215,036	8,045,001	1624.88	430.27
30	159,696,552	5,914,687	1194.61	356.26
35	112,071,157	4,150,784	838.35	289.24
40	73,406,021	2,718,742	549.12	223.77
45	43,491,799	1,610,807	325.34	152.31
50	23,131,539	856,724	173.04	94.43
55	10,508,257	389,195	78.61	47.56
60	4,150,026	153,705	31.04	24.36
65	893,741	33,102	6.69	6.69
70	0	0	0.00	0.00

TABLE 11b. Hypsographic data.

Monponsett Pond Hypsographic Data

Depth	Volume ft^3	Volume yd^3	Volume MG	Interval MG
0	164,134,731	6,079,064	1227.81	183.04
1	139,665,243	5,172,787	1044.77	172.79
2	116,566,989	4,317,296	871.98	162.10
3	94,897,612	3,514,726	709.88	150.46
4	74,783,969	2,769,777	559.42	138.16
5	56,314,388	2,085,718	421.26	117.16
6	40,652,802	1,505,659	304.10	93.85
7	28,106,478	1,040,981	210.25	76.72
8	17,851,023	661,149	133.53	61.63
9	9,611,904	355,996	71.90	46.32
10	3,420,485	126,685	25.59	21.11
11	598,987	22,185	4.48	4.46
12	2,924	108	0.02	0.02
13	37	1	0.00	0.00

Furnace Pond Hypsographic Data

Depth	Volume ft^3	Volume yd^3	Volume MG	Interval MG
0	100,255,014	3,713,149	749.96	111.05
1	85,409,850	3,163,328	638.91	103.45
2	71,581,127	2,651,153	535.46	96.82
3	58,638,558	2,171,798	438.65	89.73
4	46,642,746	1,727,509	348.91	82.41
5	35,626,032	1,319,483	266.50	63.27
6	27,168,544	1,006,242	203.23	55.34
7	19,770,439	732,238	147.89	47.56
8	13,412,508	496,760	100.33	40.35
9	8,018,304	296,974	59.98	33.29
10	3,567,456	132,128	26.69	14.60
11	1,615,583	59,836	12.09	8.28
12	508,641	18,839	3.80	3.61
13	26,357	976	0.20	0.20

TABLE 12a. Export coefficient determination.

LU/LC Export Coefficient Calculation

LU/LC, Mass	Source	Land cover reference	TP kg/ha/yr
Brushland/Succcessional	Reckhow	Mixed deciduous	0.11
		Aspen-birch	0.28
		Rotation grazing little bluestem, good cover	0.25
	EPA	Grass	0.13
	Uttormark	fallow	0.10
		Average	0.17
Cemetary	Reckhow	Central Business District	4.08
		High Density Residential Cooperatives, large amount of open grass	0.56
		Residential	1.10
		Low Density Reside, exensive grassed areas	2.70
	EPA	Multifamily Residential	0.70
		Average	1.83
Commercial	Reckhow	Commercial	0.88
		Commercial, light industry and business	0.66
	EPA	Commercial	0.80
		Average	0.78
Cranberry Bog	Uttormark	Rice	0.60
		Rice	0.11
		Ag Average	0.38
	EPA	Pasture	0.13
	Howes and Teal	Flow-through Bogs	3.40
	DeMoranville and Howes	Closed Bogs	9.90
		Average	
Cropland	Reckhow	58% row crops	3.15
		63% row crops	3.25
		35% row, 48% small grain	3.00
		Corn	2.00
			1.30
			14.00
			3.14
		Alfalfa	0.76
		Wheat	1.64
		Hay	0.64
	Uttormark	Corn	1.90
		Wheat	0.40
		Alfalfa	0.20
		Vegetables	7.60
		Average	3.07

TABLE 12b. Export coefficient determination.

LU/LC, Mass	Source	Land cover reference	TP kg/ha/yr
Forest	Reckhow	Jack Pine and Black Spruce w/ Aspen and Birch	0.31
			0.06
			0.04
		Mixed Pine and hardwood	0.28
			0.20
	EPA	Forest	0.11
		Average	0.17
Forested Wetland	Uttormark	Wetland	0.00
Golf Course	Reckhow	Central Business District	4.08
		High Density Residential Cooperatives, large amount of open grass	0.56
		Residential	1.10
		Low Density Reside, exensive grassed areas	2.70
	EPA	Multifamily Residential	0.70
		Grass	0.25
		Average	1.57
High Density Residential	Reckhow	Residential	1.10
		High Density Residential, Townhouse complex	1.10
		High density residential cooperatives	0.56
		60% of watershed as urban	1.63
	EPA	Multifamily residential	0.70
		Average	1.02
Industrial	Reckhow	78% industrial	2.67
		Industrial	0.75
		Industrial and residential	4.17
	EPA	Commercial	0.80
		Roadway	1.10
		Average	1.90
Junkyard		Used same as industrial	
	Reckhow	78% industrial	2.67
		Industrial	0.75
		Industrial and residential	4.17
	EPA	Commercial	0.80
		Roadway	1.10
		Average	1.90
Low Density Residential	Reckhow	Low density residential subdivision	0.19
		Low density residential	2.70
		Suburban	0.43
		Single family residential	0.21
	EPA	Single-family low residential	0.55
		Average	0.82

TABLE 12c. Export coefficient determination.

LU/LC, Mass	Source	Land cover reference		TP kg/ha/yr
Medium Density	EPA	Single-Family high density		0.65
	Reckhow	Residential		1.10
		60% residential		1.23
		Residential		0.60
			Average	0.90
Mining	Reckhow	Industrial		0.75
		Industrial and Residential		4.17
	EPA	Roadway		1.50
			Average	2.14
Multifamily Residential	Reckhow	Residential		1.10
		High density residential, townhouse complex		1.10
	EPA	Multifamily residential		0.70
			Average	0.97
Non-forested wetland	Uttormark	Wetland		0.00
Nursery	EPA	Forest		0.11
		Grass		0.13
	Uttormark	Apple Orchard		1.40
		Vegetable		7.60
			Average	2.31
Open Land	EPA	Grass		0.13
		Roadway		1.10
	Uttormark	Fallow		0.10
			Average	0.44
Orchard		Mostly same as nursery		
	EPA	Forest		0.11
		Grass		0.13
	Uttormark	Apple Orchard		1.40
			Average	0.55
Participation Recreation		Mix of Golf Course and Open Land		
	EPA	Grass		0.13
		Roadway		1.10
		Multifamily Residential		0.70
	Uttormark	Fallow		0.10
	Reckhow	High Density Residential Cooperatives, large amount of open grass		0.56
		Residential		1.10
		Low Density Reside, exensive grassed areas		2.70
			Average	0.91

TABLE 12d. Export coefficient determination.

LU/LC, Mass	Source	Land cover reference	TP kg/ha/yr
Pasture	EPA	Pasture	0.13
	Reckhow	Moderate dairy grazing	0.14
		Continuous grazing	3.80
		Rotation grazing	0.25
		Average	1.08
Powerline/Utility	EPA	Grass	0.13
		Roadway	1.10
		Average	0.62
Saltwater Sandy Beach	Uttormark	Wetland	0.00
Transitional		formerly urban open	
	EPA	Grass	0.13
		Roadway	1.10
	Reckhow	High density residential, townhouse complex	1.10
		Industrial	0.75
		Average	0.77
Transportation	EPA	Roadway	1.10
Urban/Public Institution		Same as medium density	
	EPA	Single-Family high density	0.65
	Reckhow	Residential	1.10
		60% residential	1.23
		Residential	0.60
		Average	0.90
Very Low Density Residential			
	EPA	Forest	0.13
		Single-family low density	0.55
	Reckhow	Single family residential	0.21
		Average	0.30
Water	Uttormark	Wetland	0.00
Water-Based Recreation	EPA	Roadway	1.10
		Wetland	0.00
		Average	0.55

TABLE 13a. Pollutant loads by LU/LC.

	LU/LC	Area		TP Load
		acres	ha	kg/yr
Furnace Pond	Brushland/Successional Total	1.43	0.58	0.10
	Commercial Total	19.64	7.95	6.20
	Cranberry Bog Total	39.62	16.03	158.72
	Forest Total	475.98	192.62	31.78
	Forested Wetland Total	105.70	42.78	0.00
	Golf Course Total	17.43	7.06	11.04
	Industrial Total	0.88	0.35	0.67
	Low Density Residential Total	171.87	69.55	56.76
	Medium Density Residential Total	402.34	162.82	145.73
	Multi-Family Residential Total	3.64	1.47	1.42
	Non-Forested Wetland Total	31.98	12.94	0.00
	Open Land Total	13.24	5.36	2.37
	Participation Recreation Total	6.63	2.68	2.45
	Pasture Total	0.91	0.37	0.40
	Powerline/Utility Total	2.53	1.02	0.63
	Transitional Total	4.17	1.69	1.30
	Urban Public/Institutional Total	5.37	2.17	1.95
	Very Low Density Residential Total	7.12	2.88	0.85
	Water Total	357.82	144.80	0.00
	Total	1668.31	675.14	422.38

	LU/LC	Area		TP Load
		acres	ha	kg/yr
Silver Lake	Brushland/Successional Total	7.00	2.83	0.49
	Commercial Total	4.44	1.80	1.40
	Cranberry Bog Total	97.26	39.36	389.66
	Cropland Total	0.44	0.18	0.54
	Forest Total	1084.70	438.96	72.43
	Forested Wetland Total	253.20	102.47	0.00
	Low Density Residential Total	355.61	143.91	117.43
	Medium Density Residential Total	63.43	25.67	22.98
	Mining Total	1.83	0.74	1.58
	Multi-Family Residential Total	10.87	4.40	4.25
	Non-Forested Wetland Total	72.74	29.44	0.00
	Open Land Total	12.13	4.91	2.18
	Participation Recreation Total	3.35	1.36	1.24
	Pasture Total	1.72	0.70	0.75
	Powerline/Utility Total	8.64	3.49	2.15
	Transitional Total	1.28	0.52	0.40
	Transportation Total	2.05	0.83	0.91
	Urban Public/Institutional Total	20.09	8.13	7.28
	Very Low Density Residential Total	66.35	26.85	7.97
	Water Total	657.80	266.20	0.00
	Total	2724.92	1102.74	633.64

TABLE 13b. Pollutant loads by LU/LC.

	LU/LC		Area		TP Load
			acres	ha	kg/yr
Monponsett Pond, East Basin	Commercial Total		20.80	8.42	6.56
	Cranberry Bog Total		168.50	68.19	675.10
	Forest Total		636.87	257.73	42.53
	Forested Wetland Total		261.50	105.83	0.00
	High Density Residential Total		17.97	7.27	7.40
	Industrial Total		3.56	1.44	2.73
	Low Density Residential Total		325.60	131.77	107.52
	Medium Density Residential Total		190.12	76.94	68.86
	Multi-Family Residential Total		32.45	13.13	12.69
	Non-Forested Wetland Total		48.88	19.78	0.00
	Nursery Total		2.43	0.98	2.27
	Open Land Total		12.84	5.20	2.30
	Participation Recreation Total		0.56	0.22	0.21
	Pasture Total		15.79	6.39	6.90
	Transitional Total		5.91	2.39	1.84
	Transportation Total		34.37	13.91	15.30
	Urban Public/Institutional Total		5.63	2.28	2.04
	Very Low Density Residential Total		15.50	6.27	1.86
	Water Total		424.16	171.65	0.00
		Total	2223.45	899.80	956.12

	LU/LC		Area		TP Load
			acres	ha	kg/yr
Monponsett Pond, West Basin	Brushland/Successional Total		4.57	1.85	0.32
	Commercial Total		22.51	9.11	7.10
	Cranberry Bog Total		276.12	111.74	1106.24
	Cropland Total		0.59	0.24	0.73
	Forest Total		442.51	179.08	29.55
	Forested Wetland Total		308.16	124.71	0.00
	Industrial Total		1.52	0.62	1.17
	Low Density Residential Total		279.14	112.96	92.18
	Medium Density Residential Total		141.36	57.20	51.20
	Multi-Family Residential Total		0.92	0.37	0.36
	Non-Forested Wetland Total		206.65	83.63	0.00
	Participation Recreation Total		3.28	1.33	1.21
	Pasture Total		4.21	1.70	1.84
	Transitional Total		1.79	0.73	0.56
	Transportation Total		27.09	10.96	12.06
	Urban Public/Institutional Total		3.38	1.37	1.22
	Very Low Density Residential Total		4.83	1.96	0.58
	Water Total		329.57	133.37	0.00
		Total	2058.19	832.92	1306.33

TABLE 14. Mass. Surface Water Quality Standards.

Parameter	Narrative Summary Class A and Class B
Dissolved Oxygen	Not < 6.0 mg/L in CWF, not <5.0 mg/L in WWF.
Temperature	<68°F based on mean daily maximum over a 7 day period for CWF. <83°F in WWF. Natural seasonal and daily variations maintained. Increase due to discharge in Class A <1.5°F. Increases due to discharge in Class B CWF stream <3°F or <5°F in WWF, in lakes <3°F.
pH	6.5 to 8.3; not more than 0.5 outside natural range.
Bacteria	At potable intakes (Class A) fecal coliform <20 cfu/100mL in any 6 month period, or total coliform <100cfu/100mL in 90% of samples in 6 months; i) At beaches *E. coli* geomean of 5 samples <126cfu/100mL, single sample <235cfu/100mL; for enterococci geomean of 5 samples <33cfu/100mL,single sample <61cfu/100mL ii): other waters and non-bathing season *E. coli* 6 month geomean <126cfu/100ml and single sample < 235cfu/100mL or for enterococci the geomean <33cfu/100mL and single sample <61cfu/100mL
Solids	Free of floating, suspended, settleable solids that would impair use, aesthetics, biota, or sediment quality
Color and Turbidity	Free from color and turbidity that would impair aesthetics or any other use
Oil and Grease	Waters free of oil and grease, petrochemicals, volatiles, or synthetic organics
Taste and Odor	None above natural origin
Additional Minimum Criteria for all Surface Waters	
Aesthetics	Free from pollutants that form deposits, debris or scum in nuisance density, objectionable odor, color, taste, turbidity, or production of nuisance aquatic life.
Bottom Pollutants	Free from pollutants that adversely affect physical or chemical nature of bottom, interrupt propagation of fish or shellfish, or impact population of non-mobile benthic organisms.
Nutrients	Free from nutrients above natural concentrations that would impact a designated use or exceed site specific criteria in a TMDL. Any discharge shall by treated the highest and best practical treatment (HBPT) for potable water and best available technology economically achievable (BAT) for other waters to protect existing uses. Nonpoint source nutrients may also require management.
Radioactivity	Should be free from radioactive substances harmful to human, animal or aquatic life, and designated uses, levels in aquatic life exceeding human consumption standards, or exceeding Massachusetts Drinking Water Regulations.
Toxic Pollutants	Free from pollutants to toxics to humans, aquatic life, and wilflife. Refer to *National Recommended Water Quality Criteria: 2002, EPA 822-R02-047.* MADEP may set site specific criteria to account for background levels. Considerations include Site Specific Criteria, Human Helath Risk Levels, Accumulation of Polluatants, and Public Notice.

TABLE 15. USEPA Ecoregion Nutrient Guidance.

Parameter	Unit	P25 Reference Conditions	
		Lakes	**Rivers**
TKN	mg/L	0.38	0.37
$NO_2 + NO_3$-N	mg/L	0.06	0.07
TN (calculated)	mg/L	0.44	0.44
TN (reported)	mg/L	0.32	0.71
TP	µg/L	8	31.25
Secchi *	m	4.5	-
Turbidity	NTU	-	1.94
Turbidity	FTU	-	3.04
Turbidity	JCU	-	3.88
Chlorophyll *a(F)*	µg/L	2.9	0.44
Chlorophyll *a (S)*	µg/L	1.9	3.75
Chlorophyll *a (T)*	µg/L	12.2	-

TN calculated - sum of TKN + NO_2 + NO_3

* - Secchi value is P75

F - fluorometric, *S* - spectrophotometric, *T*- Trichromatic for Chlorophyll *a, b, c*

NTU- nephelometric turbidity unit, FTU-formazin turbidity unit, JCU-Jackson candle units

TABLE 16. Waterbody Designation/Classification

Water Body	Class	Qualifier	Basin	Watershed
Silver Lake	A	Public Water Supply	South Coastal	Jones River
Silver Lake is the primary water source for Brockton Water System (BWS). The lake lies within the Jones River watershed, but receives inflow from both the Taunton River and the North River watersheds which requires artificial diversion/management of the water supply. Consumptive use of the water occurs primarily within the Taunton River watershed.				
Forge Pond	A	Public Water Supply	South Coastal	Jones River
Forge Pond is impoundment of the Jones River and an extension of Silver Lake. At high lake stages, it maintains a common stage with Silver Lake. At lower stages, it is separated from Silver Lake by a berm, formerly the outlet to Jones River.				
Tubbs Meadow Brook	A	Public Water Supply	South Coastal	Jones River
The diversion at Furnace Pond/Gorham Mill Pond is routed through Tubbs Meadow Brook to Silver Lake.				
Furnace Pond	A	Public Water Supply	South Coastal	North River
Furnace Pond is located in the North River watershed and discharges to this system via Herring Brook, but water is diverted for BWS across the watershed boundary and into the Jones River watershed where it is discharged to Silver Lake.				
Oldham Pond	A	Public Water Supply	South Coastal	North River
Oldham Pond is tributary to Furnace Pond, but the ponds are maintained at a common stage.				
Gorham Mill Pond	A	Public Water Supply	South Coastal	North River
Gorham Mill Pond is a small pond located at the outlet of Furance Pond. The pond is an impoundment of Herring Brook and that dam controls the stage of both Furnace Pond and Oldham Pond. There is a water supply diversion in the pond that discharges to Silver Lake via Tubbs Meadow Brook.				
Monponsett Pond	A	Public Water Supply	Taunton River	Taunton River
Monponsett Pond is actually a binary system with two basins of roughly equal dimension joined by a culvert that maintains the basins at the same stage. The system discharges from the west basin to Stump Brook within the Taunton River watershed. A water supply diversion in the east basin discharges to Silver Lake, located within the Jones River watershed.				
Brockton Reservoir	A	Public Water Supply	Taunton River	Taunton River
Brockton Reservoir (aka Avon Reservoir) is a water supply reservoir located just outside the City of Brockton, approximately 13 miles northwest of the other project waters.				
Jones River (source to Wapping Road)	B	Warm Water, High Quality Water	Jones River	Jones River
The Jones River, from its source at Silver Lake/Forge Pond to Wapping Road (the site of a recent dam removal), is a Class B water. Several miles downstream the river becomes tidal.				
Herring Brook	B	Outstanding Water Resource	South Coastal	North River
Herring Brook is the natural outlet channel of Furnace Pond/Gorham Mill Pond. It is the only project waterbody designated as an Outstanding Water Resource. Herring Brook confluences with the Indian Head River within the North River watershed.				
Stump Brook	B	High Quality Water	Taunton River	Taunton River
Stump Brook is the natural outlet to Monponsett Pond. Stump Brook is impounded in several locations before discharging to the Satucket River in the Taunton River watershed.				